

Steam Nozzle (a)

→ Steam nozzle is a device of varying cross-section used to convert the enthalpy or heat energy into kinetic energy

→ functions :-

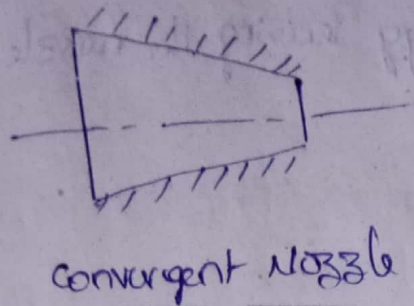
1. It is used to convert pressure energy of steam into kinetic energy
2. In impulse turbine, nozzle is used to direct the high velocity steam on to a rotating rotor
3. In reaction turbine, the nozzles are used to rotate the blade

→ Applications :-

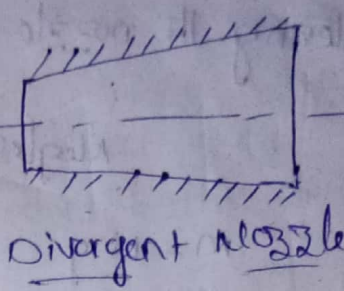
1. It is used in the steam turbines & gas turbines (for converting the) to obtain high velocity stream of working fluid
2. for metering the flow of fluid in a pipeline
3. used in the ejectors for the removal of the air from the condenser
4. It is used in the steam injector for pumping feed water to the boiler

→ Types of nozzles :-

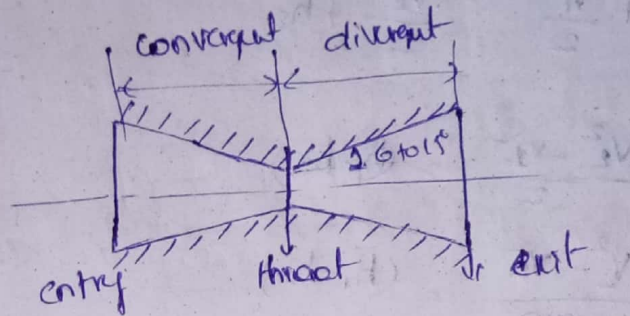
1. Convergent nozzle
2. Divergent nozzle
3. Convergent - Divergent nozzle



convergent nozzle

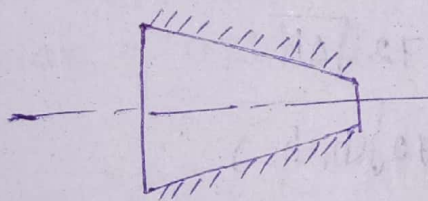


divergent nozzle



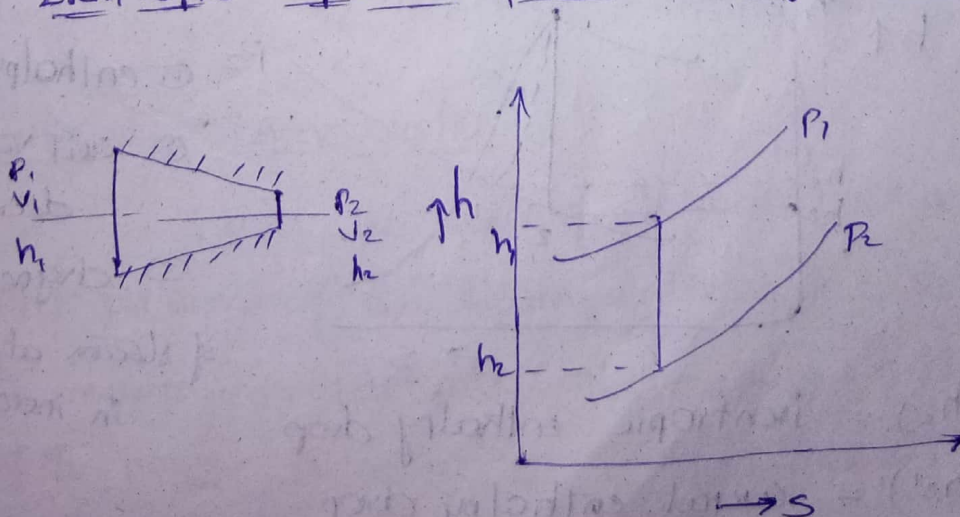
convergent-divergent nozzle

→ flow of steam through a nozzle :-



1. adiabatic expansion of steam (friction is consider)
2. Isentropic expansion of steam (friction less adiabatic process)

→ Isentropic expansion of steam through nozzle :-



consider nozzle as open system

energy entering the nozzle = energy leaving the nozzle + loss

Neglect losses

$$m = 1 \text{ kg}$$

$$h_1 + \frac{v_1^2}{2} = \frac{v_2^2}{2} + h_2$$

$$\frac{v_2^2 - v_1^2}{2} = (h_1 - h_2)$$

$$\frac{v_2^2 - v_1^2}{2000} = (h_1 - h_2)$$

$$v_2^2 - v_1^2 = 2000 (h_1 - h_2)$$

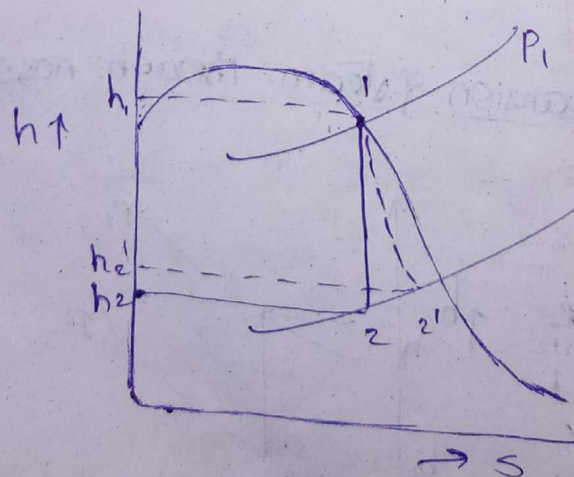
$$v_2^2 - v_1^2 = 2000 (\Delta h)$$

$$v_2 = \sqrt{2000 (\Delta h) + v_1^2} \quad (\because v_1 = 0)$$

$$v_2 = 44.72 \sqrt{\Delta h}$$

$$v_2 = 44.72 \sqrt{(h_1 - h_2)}$$

→ Adiabatic expansion of steam through nozzle :-



Effects due to Friction

- ① enthalpy drop
- ② exit velocity decreases
- ③ dryness fraction of steam at exit increases

$(h_1 - h_2)$ = isentropic enthalpy drop

$(h_1 - h_{2'})$ = actual enthalpy drop

nozzle efficiency (η) nozzle coefficient (C) friction factor (k)

$$\eta_N \text{ (or) } k = \frac{\text{useful heat drop}}{\text{isentropic heat drop}}$$

$$k = \frac{h_1 - h_2'}{h_1 - h_2}$$

$$V_2 = 44.72 \sqrt{h_1 - h_2'}$$

$$V_2 = 44.72 \sqrt{k(h_1 - h_2)}$$

→ velocity coefficient :-

It is the ratio of actual exit velocity to the exit velocity when the flow is isentropic b/w two pressures. It is also defined as square of nozzle η .

$$C_v = \frac{\text{Actual exit velocity}}{\text{Isentropic exit velocity}} = \frac{V_2'}{V_2}$$

$$C_v = \sqrt{\text{Nozzle efficiency}}$$

$$C_v = \sqrt{\frac{\text{useful enthalpy drop}}{\text{isentropic enthalpy drop}}}$$

→ critical pressure ratio

It is the ratio of throat pressure to the inlet pressure of the steam entering into the nozzle for maximum discharge. The pressure of the throat of the nozzle is called as critical pressure.

If the expansion of the steam in the nozzle is greater than the throat pressure then we have to use divergent portion of the nozzle.

* Discharge flowing through a pipe or nozzle per second is given by

$$m = A \sqrt{\frac{2n}{n-1} \times \frac{P_1}{v_1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{2}{n}} - \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n}} \right]}$$

$$m \text{ is a function of } \left[\left(\frac{P_2}{P_1} \right)^{\frac{2}{n}} - \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n}} \right]$$

derive right hand side term w.r.to (P_2/P_1) and equate to zero i.e.

$$\frac{d}{d(P_2/P_1)} \left[\left(\frac{P_2}{P_1} \right)^{\frac{2}{n}} - \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n}} \right] = 0$$

$$\frac{2}{n} \left(\frac{P_2}{P_1} \right)^{\frac{2}{n}-1} - \frac{n+1}{n} \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n}-1} = 0$$

$$\frac{2}{n} \left(\frac{P_2}{P_1} \right)^{\frac{2-n}{n}} - \frac{n+1}{n} \left(\frac{P_2}{P_1} \right)^{\frac{n+1-n}{n}} = 0$$

$$\frac{2}{n} \left(\frac{P_2}{P_1} \right)^{\frac{2-n}{n}} = \frac{n+1}{n} \left(\frac{P_2}{P_1} \right)^{\frac{1}{n}}$$

$$\left(\frac{P_2}{P_1} \right)^{\frac{2-n}{n}} \times \left(\frac{P_2}{P_1} \right)^{-\frac{1}{n}} = \frac{n+1}{n} \times \frac{n}{2}$$

$$\left(\frac{P_2}{P_1} \right)^{\frac{2-n}{n} - \frac{1}{n}} = \frac{n+1}{2}$$

$$\left(\frac{P_2}{P_1} \right)^{\frac{1-n}{n}} = \frac{n+1}{2}$$

$$(P_2/P_1) = \left(\frac{n+1}{2}\right)^{n/(1-n)}$$

$$(P_2/P_1) = \left(\frac{n+1}{2}\right)^{\frac{-n}{-(1-n)}}$$

$$(P_2/P_1) = \left(\frac{n+1}{2}\right)^{\frac{n}{-1+n}}$$

$$\boxed{(P_2/P_1) = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}}$$

→ values of critical pressure ratio :-

* for steam initially superheated ($n = 1.3$)

$$(P_2/P_1) = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

$$(P_2/P_1) = \left(\frac{2}{1.3+1}\right)^{\frac{1.3}{1.3-1}}$$

$$(P_2/P_1) = 0.545$$

* when steam is initially dry & saturated ($n = 1.135$)

$$(P_2/P_1) = \left(\frac{2}{1.135+1}\right)^{\frac{1.135}{1.135-1}}$$

$$(P_2/P_1) = 0.577$$

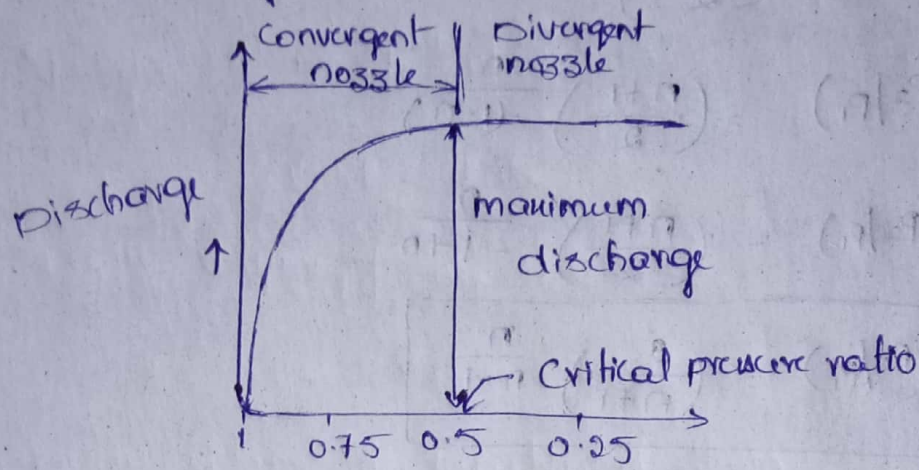
* when steam is initially wet ($n = 1.035 + 0.1x$)

* when gas is expanded in nozzle ($n = 1.4$)

$$(P_2/P_1) = \left(\frac{2}{1.4+1}\right)^{\frac{1.4}{1.4-1}}$$

$$(P_2/P_1) = 0.528$$

→ Significance of critical pressure ratio



Pressure ratio → (P_2/P_1)

→ Condition for max discharge through a nozzle :-

Discharge through a nozzle per sec is given by

$$m = A \sqrt{\frac{2n}{n-1} \times \frac{P_1}{v_1} \left[(P_2/P_1)^{2/n} - (P_2/P_1)^{\frac{n+1}{n}} \right]}$$

Substitute critical pressure ratio (P_2/P_1) for max discharge

$$m_{\max} = A \sqrt{\frac{2n}{n-1} \times \frac{P_1}{v_1} \left[\left(\frac{2}{n+1} \right)^{\frac{n}{n-1}} - \left[\left(\frac{2}{n+1} \right)^{\frac{n}{n-1}} \right]^{\frac{n+1}{n}} \right]}$$

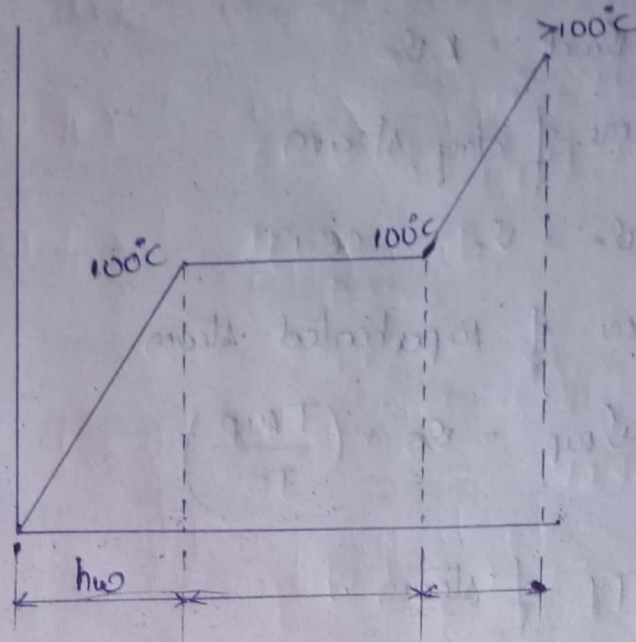
$$m_{\max} = A \sqrt{\frac{2n}{n-1} \times \frac{P_1}{v_1} \left[\left(\frac{2}{n+1} \right)^{\frac{2}{n-1}} - \left(\frac{2}{n+1} \right)^{\frac{n+1}{n-1}} \right]}$$

$$= A \sqrt{\frac{2n}{n-1} \times \frac{P_1}{v_1} \left(\frac{2}{n+1} \right)^{\frac{2}{n-1}} \left[1 - \left(\frac{2}{n+1} \right) \right]}$$

$$= A \sqrt{\frac{2n}{n-1} \times \frac{P_1}{v_1} \left(\frac{2}{n+1} \right)^{\frac{2}{n-1}} \left[\frac{n-1}{n+1} \right]}$$

$$= A \sqrt{2n \times \frac{P_1}{v_1} \left(\frac{2}{n+1} \right)^{\frac{2}{n-1}} \left(\frac{1}{n+1} \right)}$$

→ continuity equation :-



enthalpy of steam :-

(i) enthalpy of wet steam

$$H_{wet} = h_w + xL$$

h_w = sensible heat (kJ/kg)

x = dryness fraction

L = latent heat (kJ/kg)

(ii) specific enthalpy of dry steam

$$H_s = h_w + L \quad (x=1)$$

(iii) specific enthalpy of superheated steam

$$\begin{aligned} H_{sup} &= h_s + c_p (t_{sup} - t_s) \\ &= h_w + L + c_p (t_{sup} - t_s) \end{aligned}$$

c_p = sp. heat of superheated steam = 2.1 kJ/kg.K

t_{sup} = super heated temp °C

t_s = saturated temp in °C

* Specific volume of steam :-

(i) Specific volume of wet steam

$$v_{wet} = x \cdot v_s$$

(ii) Specific volume of dry steam

$$v_s = v_s \quad (x=1)$$

(iii) Specific volume of superheated steam

$$v_{sup} = v_s \times \left(\frac{T_{sup}}{T_s} \right)$$

* Specific entropy of steam :-

(i) Specific entropy of wet steam

$$\phi_{wet} = \phi_w + x \phi_e$$

ϕ = entropy of water (kJ/kg.K)

ϕ_e = entropy of evaporation (kJ/kg.K)

(ii) Specific entropy of dry steam

$$\phi_s = \phi_w + \phi_e$$

(iii) sp. entropy of super heated steam

$$\phi_{sup} = \phi_s + c_p \ln \left(\frac{T_{sup}}{T_s} \right)$$

Estimate the mass flow rate of the steam in a nozzle with the following data, inlet pressure & temp is 10 bar & 220°C, back pressure is 0.5 bar, throat dia is 12 mm

sol Given data

inlet pressure $P_1 = 10 \text{ bar}$

temp $t_1 = 220^\circ\text{C}$

back pressure $P_3 = 0.5 \text{ bar}$

throat dia $d_2 = 12 \text{ mm} = 0.012 \text{ m}$

mass flow rate = ?

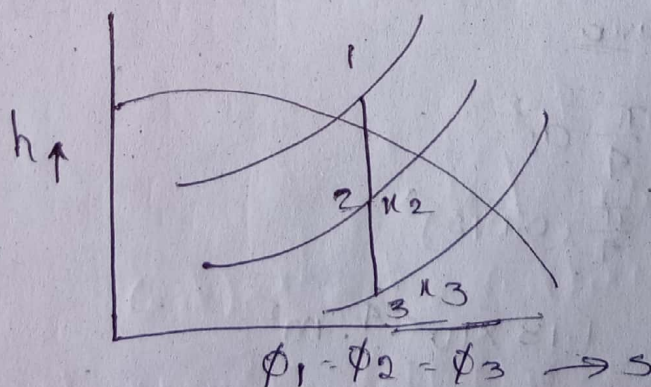
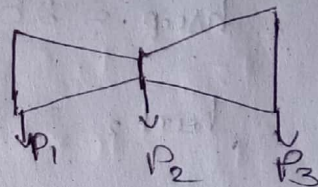
critical pressure ratio

$$P_2/P_1 = \left(\frac{2}{n+1} \right)^{n/n-1}$$

$$= \left(\frac{2}{1.3+1} \right)^{1.3/0.3}$$

$$= 0.545$$

$$P_2 = 0.545 \times 10 = 5.45 \text{ bar}$$



$$\phi_1 = \phi_2$$

$$\phi_{\text{sup}} = \phi_{\text{wet 2}}$$

$$6.692 = 1.892 + x_2(4.899)$$

$$x_2 = \frac{6.692 - 1.892}{4.898} = 0.92$$

$$\phi_1 = \phi_3$$

$$\phi_{\text{sup}} = \phi_{\text{wet } 3}$$

$$6.692 = 1.091 + x_3 (6.504)$$

$$x_3 = \frac{6.692 - 1.091}{6.504}$$

$$x_3 = 0.86$$

from steam tables

$$h_1 = h_{\text{sup}} = 2826.8 \text{ kJ/kg}$$

$$h_2 = h_{\text{wet } 2} = 1653.8 + 0.92 \times 2697.4$$

$$= 2688.27 \text{ kJ/kg}$$

throat velocity

$$v_2 = 44.72 \sqrt{h_1 - h_2}$$

$$= 44.72 \sqrt{(2826.8) - (2688.27)}$$

$$= 526.3 \text{ m/s}$$

throat area

$$A_2 = \frac{\pi}{4} d_2^2$$

$$= \frac{\pi}{4} (0.012)^2$$

$$= 1.13 \times 10^{-4} \text{ m}^2$$

S.P of wet steam

$$Q_{\text{wet}} = x \cdot V_1$$

$$= 0.92 \times 0.398 = 0.33 \text{ m}^3/\text{kg}$$

$$\begin{aligned} \text{mass } m_2 &= \frac{A_2 v_2}{v_{\text{wet}}} \\ &= \frac{1.130 \times 10^{-4} \times 526.3}{0.33} \\ &= \underline{\underline{0.13 \text{ kg/s}}} \end{aligned}$$

1. Steam at a pressure of 10 bar and 0.9 dry discharge at through a nozzle having throat area of 450 mm^2 by the back press. is 1 bar. find final velocity of the steam cross section area of a nozzle at exit where max discharge.

sd Given data

steam pressure $p_1 = 10 \text{ bar}$

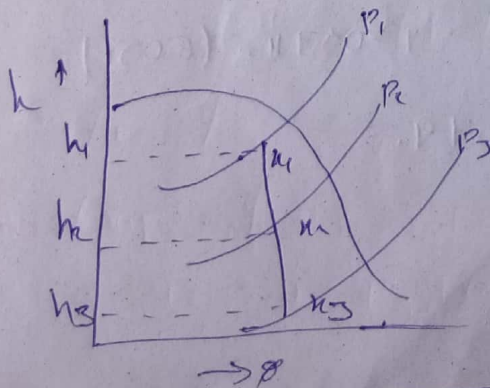
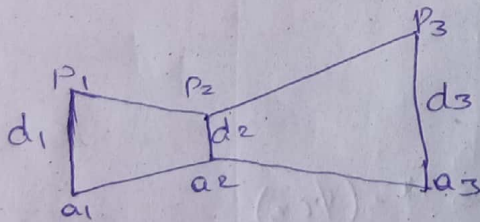
dryness fraction $x = 0.9$

throat area $a_2 = 450 \text{ mm}^2$

back press: $p_3 = 1 \text{ bar}$

final velocity $v_3 = ?$

cross section area of exit $a_3 = ?$



critical pressure ratio

$$\frac{P_2}{P_1} = \left(\frac{2}{n+1} \right)^{n/(n-1)}$$

$$n = 1.035 + 0.1K$$

$$= 1.035 + 0.1(0.9)$$

$$= 1.125$$

$$P_2/P_1 = \left(\frac{2}{1.125+1} \right)^{\frac{1.125}{1.125-1}}$$

$$P_2/P_1 = 0.579$$

$$P_2 = P_1 \times 0.579$$

$$P_2 = 10 \times 0.579 = \underline{5.8 \text{ bar}}$$

$$\phi_1 = \phi_2$$

$$\phi_{wet1} = \phi_{wet2}$$

$$\phi_{w1} + \kappa_1 \phi_{e1} = \phi_{w2} + \kappa_2 \phi_{e2}$$

$$2.138 + 0.9(4.445) = 1.931 + \kappa_2(4.851)$$

$$\kappa_2 = 0.86$$

$$\phi_1 = \phi_3$$

$$\phi_{wet1} = \phi_{wet3}$$

$$\phi_{w1} + \kappa_1(\phi_{e1}) = \phi_{w3} + \kappa_3(\phi_{e3})$$

$$2.138 + 0.9(4.445) = 1.303 + \kappa_3(6.057)$$

$$\kappa_3 = 0.79$$

2. A reheat cycle has steam generated at 50 bar, 500°C for being tends to high pressure turbine and expanded upto 5 bar before supplied to low pressure turbine. Steam enters at 5 bar, 400°C into low pressure turbine after being reheated in the boiler. Steam finally enters condenser at 0.05 bar and subsequently feed water send to the boiler. Determine cycle efficiency & specific heat consumption.
3. A boiler is to provided 7000 kg/hr of steam which superheated by 40°C at a pressure of 20 bar. The temp of the feed water is 50°C . If the thermal η of the boiler is 75%, how much fuel oil will be consumed in 1 hr? The calorific value of the oil is 45000 kJ/kg. Take specific heat of the superheated steam as 2.093 kJ/kg.K. & also calculate the equivalent evaporation from and at 100°C .
4. Steam at 15 bar, 300°C expands in a nozzle till it pressure falls to 1 bar. If 12% of the isentropic heat drop is lost in friction. Find out the mass of the steam passing through a nozzle of exit diameter is 1.5 cm, neglect the initial velocity of the steam.
5. A chimney of 24 m height is used to produce a natural draught at flue gas temp is 300°C and ambient temp is 25°C . The air supplied

is 20 kg/kg of fuel burnt. Find the

- exit theoretical draught produced in mm of water
- velocity of hot gases passing through the chimney if 50% of the theoretical draught is lost in friction.

4 sol

Given data

$$P_1 = 15 \text{ bar}$$

$$T_1 = 300^\circ\text{C}$$

$$P_2 = 1 \text{ bar}$$

$$\eta_{uo} = 100\% - 12\% = 88\% = 0.88$$

$$m_2 = ?$$

$$d_2 = 1.5 \text{ cm}$$

$$V_1 = 0$$

$$\eta_N = \frac{h_1 - h_2'}{h_1 - h_2}$$

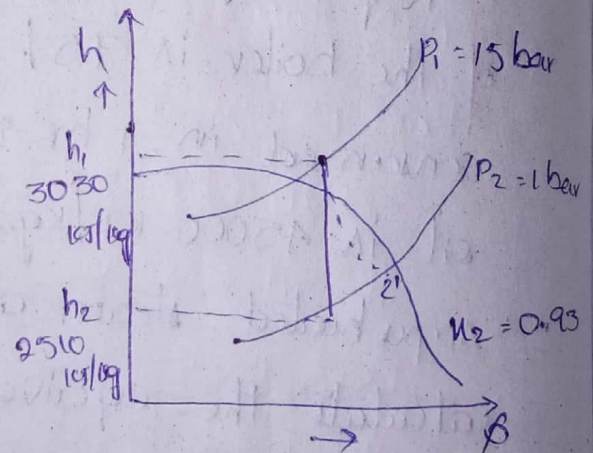
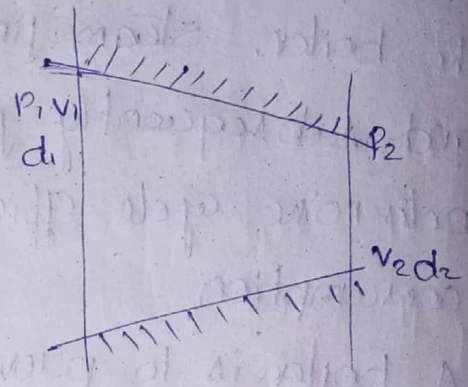
$$h_1 - h_2' = \eta_N (h_1 - h_2)$$

$$V_2 = 44.72 \sqrt{h_1 - h_2'}$$

$$V_2 = 44.72 \sqrt{\eta_N (h_1 - h_2)}$$

$$V_2 = 44.72 \sqrt{0.88 (3030 - 2510)}$$

$$V_2 = 960 \text{ m/s}$$



exit area

$$\begin{aligned} A_2 &= \frac{\pi}{4} d_2^2 \\ &= \frac{\pi}{4} (0.015)^2 \\ &= 1.767 \times 10^{-4} \text{ m}^2 \end{aligned}$$

from

$$h_1 - h_2' = \eta_N (h_1 - h_2)$$

$$3030 - h_{wet2}' = 0.88 (3030 - 2510)$$

$$3030 - (h_{w2} + \lambda_2 h_{f2}) = 0.88 (3030 - 2510)$$

$$3030 - (417.5 + \lambda_2' (2257.9)) = 0.88 (3030 - 2510)$$

$$\boxed{\lambda_2' = 0.95}$$

$$m = \frac{A_2 v_2}{v_2}$$

$$m = \frac{A_2 v_2}{v_{wet2}} \Rightarrow \frac{A_2 v_2}{\lambda_2' v_{s2}}$$

$$\frac{1.767 \times 10^{-4} \times 960}{0.95 \times 1.6938}$$

$$\boxed{m = 0.1054 \text{ kg}}$$

3rd

→ η_{thermal} of the boiler :-

It is the ratio of heat utilized to form steam by heat released by the fuel.

$$\eta_{\text{ther}} = \frac{m_s (h_2 - h_{w1})}{m_f \times \text{cv}} \times 100$$

$$m = m_s / m_f \quad (\text{kg/kg})$$

m_s = mass of steam generated kg/hr

m_f = mass of fuel kg/hr

$$\eta_{\text{ther}} = \frac{m (h_2 - h_{w1})}{C_v} \times 100$$

→ equivalent evaporation :-

$$m_e = \frac{m_s (h_2 - h_{w1})}{2256.9} \quad \text{kg/hr}$$

m_s = mass of steam generated/hr (kg/hr)

h_2 = enthalpy of steam kJ/kg

h_{w1} = feed water enthalpy (kJ/kg)

$$m_e = \frac{m (h_2 - h_{w1})}{2256.9} \quad \text{kg/kg of fuel}$$

Given data

$m_s = 7000$ kg/hr of steam

$C_p (t_{\text{sup}} - t_s) = 40^\circ\text{C}$

$P_1 = 20$ bar

$t_{w1} = 60^\circ\text{C}$

$\eta_{\text{th}} = 75\% \Rightarrow 0.75$

$m_f = ?$ in 1 hr

$C_v = 45000$ kJ/kg

$m_e = 100^\circ\text{C}$ at = ?

$C_p = 2.093$ kJ/kg $\cdot$ °C

at $p_1 = 20 \text{ bar} \rightarrow t_s = 212.4^\circ\text{C}$

$$\rightarrow \eta_{th} = \frac{m_s (h_2 - h_{w1})}{m_f \times c.v} \times 100$$

$$c_p \times (t_{sup} - t_s) = 40^\circ\text{C}$$

$$2.093 (t_{sup} - 212.4) = 40$$

$$t_{sup} = 231.5^\circ\text{C}$$

$$h_2 = h_{sup2} = h_{s2} + c_p (t_{sup} - t_s)$$

$$h_2 = 2797.2 + 2.093 \times 40$$

$$h_2 = 2837.2 \text{ kJ/kg}$$

$$\rightarrow 0.75 = \frac{7000 (2837.2 - 253.1)}{m_f \times 45000}$$

$$m_f = 536.18 \text{ kg/hr}$$

at $t_w = 60^\circ \rightarrow h_{w1} = 251.1 \text{ kJ/kg}$

at kg/kg

$$\rightarrow m = m_s / m_f = 7000 / 536.18 = 13.05 \text{ kg/kg}$$

$$\rightarrow m_e = \frac{m_s (h_2 - h_{w1})}{2256.9}$$

$$m_e = \frac{7000 (2837.2 - 251.1)}{2256.9} = 8021.04 \text{ kg/hr}$$

$$m_e = \frac{m (h_2 - h_{w1})}{2256.9}$$

$$= \frac{13.05 (2837.2 - 251.1)}{2256.9} = 14.95 \text{ kg/kg}$$

5 sol given data

height $H = 24 \text{ m}$

flue gas temp $t_2 = 300^\circ\text{C}$

ambient temp $t_1 = 25^\circ\text{C}$

$m = 20 \text{ kg/kg of fuel burnt}$

50% of theoretical draught is losses

$$(i) \quad h = 353 H \left[\frac{1}{T_1} - \frac{m_a + 1}{m_a t_2} \right]$$

$$h = 353 (24) \left[\frac{1}{298} - \frac{20 + 1}{20(573)} \right]$$

$$h = 12.90 \text{ mm of water}$$

(ii) velocity of flue gases

Equivalent gas head

$$H_1 = H \left[\frac{m_a}{m_a + 1} \times \frac{T_2}{T_1} - 1 \right]$$

$$= 24 \left[\frac{20}{20 + 1} \times \frac{573}{298} - 1 \right]$$

$$= 21.09 \text{ m}$$

available head

$$0.5 \times 21.09 = 10.5 \text{ m}$$

velocity of flue gases

$$= \sqrt{2gH_1}$$

$$= \sqrt{2 \times 9.81 \times 10.5}$$

$$= 14.38 \text{ m/s}$$

259/ Given data

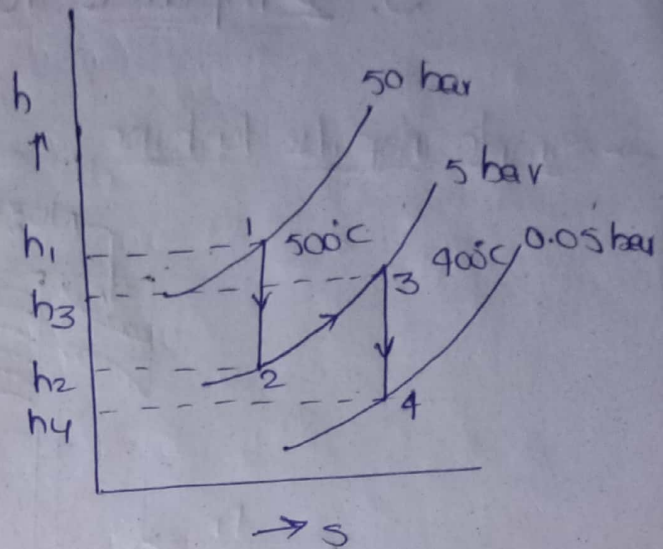
$$P_1 = 50 \text{ bar}$$

$$T_1 = 500^\circ\text{C}$$

$$P_3 = 5 \text{ bar}$$

$$T_3 = 400^\circ\text{C}$$

$$P_4 = 0.05 \text{ bar}$$



$$h_1 = 3440 \text{ kJ/kg}$$

$$h_2 = 2820 \text{ kJ/kg}$$

$$h_3 = 3260 \text{ kJ/kg}$$

$$h_4 = 2390 \text{ kJ/kg}$$

$$h_4 = h_{f4} \text{ from steam tables}$$

$$h_{f4} = 137.8 \text{ kJ/kg}$$

$$\begin{aligned} \text{(i) Rankine cycle } (\eta) &= \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_3 - h_2) + (h_1 - h_{f4})} \\ &= \frac{(3440 - 2820) + (3260 - 2390)}{(3260 - 2820) + (3440 - 137.8)} \\ &= 0.398 \text{ (or) } 39.8\% \end{aligned}$$

(ii) Specific Steam Consumption

$$1 \text{ kWh} = 3600 \text{ kJ}$$

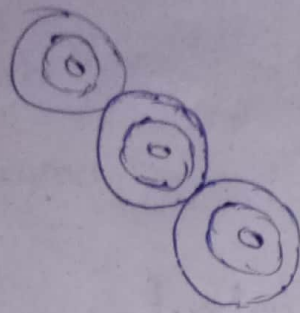
$$sfc = \frac{1 \text{ kWh}}{(h_1 - h_2) + (h_3 - h_4)}$$

$$\frac{\text{kJ/s} \times 8}{\text{kJ}}$$

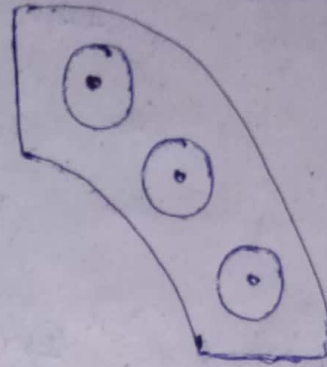
$$= \frac{3600}{(3440 - 2820) + (3260 - 2390)}$$

$$= 2.416 \text{ kg/kWh}$$

1. cam type



2. cannular type



3. annular type



1. In an air standard regenerative gas turbine cycle the pressure ratio is 5. Air enters the compressor at 1 bar, 300 K and leaves at 490 K. The max temp in the cycle is 1000 K. Calculate cycle efficiency, given that efficiency of regenerator & the turbine are 80%. Assume ratio of specific heat as 1.4

sol

Given data

$$P_2/P_1 = 5$$

$$P_1 = 1 \text{ bar}$$

$$T_1 = 300 \text{ K}$$

$$T_2' = 490 \text{ K}$$

$$\eta_{\text{turbine}} = \frac{\text{Actual work output}}{\text{Isentropic work output}} \times 100$$

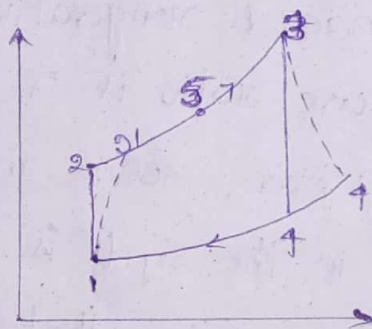
$$= \frac{T_3 - T_4'}{T_3 - T_4} \times 100$$

$$\eta_{\text{comp}} = \frac{\text{Isentropic work output}}{\text{Actual work output}} \times 100$$

$$= \frac{T_2 - T_1}{T_2' - T_1} \times 100$$

$$\text{heat supplied } Q = m c_p (T_3 - T_2') \quad (\text{without regenerator})$$

$$Q = m c_p (T_3 - T_5) \quad (\text{with regenerator})$$



$$\eta_{\text{th}} = \frac{\text{Net work}}{\text{heat supplied}} \times 100$$

$$\eta_{\text{th}} = \frac{\text{Turbine work} - \text{comp work}}{\text{heat supplied}} \times 100$$

$$\eta_{\text{th}} = \frac{W_T - W_c}{Q_s} \times 100$$

$$\eta_{\text{th}} \uparrow, Q_s \downarrow$$

contin

$$T_3 = 1000 \text{ K}$$

$$\eta_{\text{turb}} = 80\% = 0.80$$

$$\eta_{\text{regenerator}} = 80\% = 0.80$$

$$\gamma = 1.4$$

cycle efficiency = ?

$$\begin{aligned} P_1 = P_4 & \left\{ \begin{array}{l} 1 \text{ bar} \\ 5 \text{ bar} \end{array} \right. \\ P_2 = P_3 & \end{aligned}$$

1-2 : Isentropic compression

$$\left(\frac{T_2}{T_1} \right)^{\frac{1}{\gamma}-1} = (P_2/P_1)^{\frac{1}{\gamma}}$$

$$\left(\frac{T_2}{T_1} \right) = (P_2/P_1)^{\frac{\gamma}{\gamma-1}}$$

$$T_2 = (5)^{1.4-1/1.4} \times 300$$

$$T_2 = 475 \text{ K}$$

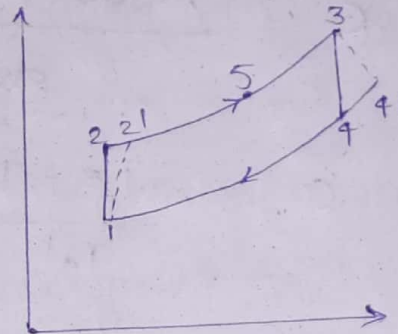
3-4 : Isentropic expansion

$$\left(\frac{T_3}{T_4} \right)^{\frac{1}{\gamma}-1} = (P_3/P_4)^{\frac{1}{\gamma}}$$

$$\frac{1000}{T_4} = (5)^{1.4-1/1.4}$$

$$T_4 = \frac{1000}{(5)^{0.4/1.4}}$$

$$T_4 = 631.48 \text{ K}$$



$$\eta_{\text{turb}} = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$0.8 = \frac{1000 - T_4'}{1000 - 631.48}$$

$$T_4' = 704.8 \text{ K}$$

$$\epsilon = \frac{\text{Actual heat exchanger or transferred}}{\text{available heat}}$$

$$\epsilon = \frac{T_5 - T_2'}{T_4' - T_2'}$$

$$0.8 = \frac{T_5 - 490}{704.8 - 490}$$

$$T_5 = 661 \text{ K}$$

Turbine work

$$W_T = m c_p (T_3 - T_4')$$

$$= 1 \times 1.005 (1000 - 704.8)$$

$$= 296.6 \text{ kJ/kg}$$

compressor work

$$W_c = m c_p (T_2' - T_1)$$

$$= 1 \times 1.005 (490 - 300)$$

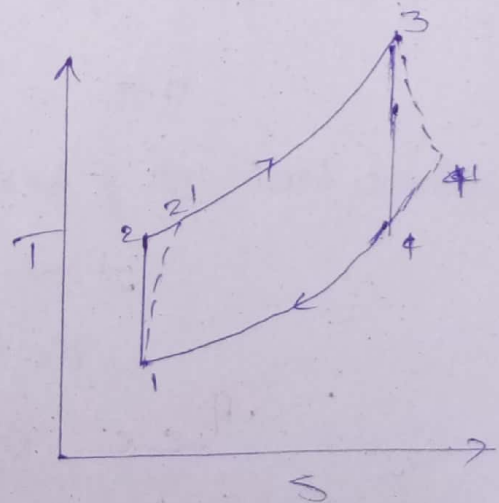
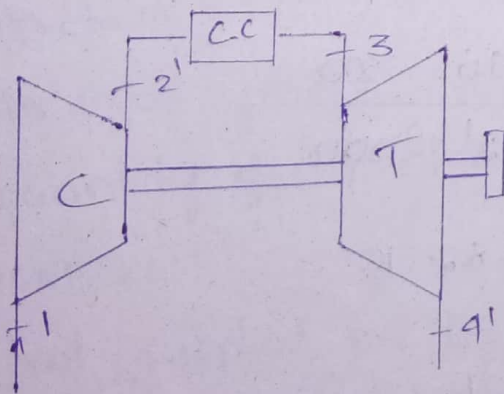
$$= 190.95 \text{ kJ/kg}$$

$$\begin{aligned}\text{heat supplied } Q &= m c_p (T_3 - T_5) \\ &= 1 \times 1.005 (1000 - 661.2) \\ &= 340.49 \text{ kJ/kg}\end{aligned}$$

$$\begin{aligned}\eta_{\text{cycle}} &= \frac{W_T - W_C}{Q_5} \times 100 \\ &= \frac{296.6 - 190.95}{340.49} \times 100 \\ &= 31.02\%\end{aligned}$$

2. Find the required air-fuel ratio in a gas turbine where turbine & compressor efficiencies are 85% & 80%. max cycle temp is 875°C . The working fluid taken as air which enters the compressor at 1 bar & 27°C . The pressure ratio is 4. calorific value of the fuel is 42000 kJ/kg. There is a loss of 10% of calorific value in the combustion chamber.

sd



$$\eta_{\text{turb}} = 0.85$$

$$\eta_{\text{com}} = 0.8$$

$$T_3 = 875^\circ\text{C} + 273 = 1148\text{K}$$

$$P_1 = 1\text{ bar}$$

$$T_1 = 27^\circ\text{C} + 273 = 300\text{K}$$

$$P_2/P_1 = 4$$

$$C_v = 42000\text{ J/kg}$$

10% loss in combustion chamber

$$\left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = (P_2/P_1)^{\frac{1}{\gamma}}$$

$$T_2 = (4)^{0.4/1.4} \times 300$$

$$T_2 = 446\text{ K}$$

$$\eta_{\text{com}} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.8 = \frac{446 - 300}{T_2' - 300}$$

$$T_2' = 482\text{ K}$$

$$\eta_{\text{c.c.}} = 90\% = 0.9$$

$$\eta_{\text{cc}} = \frac{(m_a + m_f) \times c_p (T_3 - T_2')}{m_f \times C_v}$$

$$\eta_{cc} \times c_v \times m_f = (m_a + m_f) \times c_p (T_3 - T_2')$$

$$\eta_{cc} \times c_v = \frac{(m_a + m_f)}{m_f} \times c_p (T_3 - T_2')$$

$$c_v = \left(\frac{m_a}{m_f} + 1 \right) \times \frac{c_p (T_3 - T_2')}{\eta_{cc}}$$

$$42000 = \left(\frac{m_a}{m_f} + 1 \right) \times \frac{1.005 (1148 - 482)}{0.9}$$

$$\frac{m_a}{m_f} + 1 = 56.474$$

$$\frac{m_a}{m_f} = 55.474$$

3. In a constant pressure open cycle gas turbine air enters at 1 bar & 20°C and leaves the compressor at 5 bar. use the following data.
 Temperature of gases entering the turbine is 680°C,
 pressure loss in the combustion chamber is 0.1 bar,
 efficiency of the compressor is 85%, turbine η is 80%.
 $\eta_{comp. ch}$ is 85%. $\therefore \gamma = 1.4$, $c_p = 1.024 \text{ kJ/kg.K}$

for air & gas, find

- (i) quantity of air circulations if the plant develop 1065 kW
 - (ii) heat supplied per kg of air
 - (iii) thermal efficiency of the cycle
- mass of the fuel is neglected.

30 Given data

$$P_1 = 1 \text{ bar}$$

$$T_1 = 20 + 273 = 293 \text{ K}$$

$$P_2 = 5 \text{ bar}$$

$$T_3 = 680 + 273 = 953 \text{ K}$$

$$P_3 = 5 - 0.1 = 4.9 \text{ bar}$$

$$\eta_{\text{comp}} = 85\% = 0.85$$

$$\eta_{\text{turb}} = 80\% = 0.80$$

$$\eta_{\text{c.c.}} = 85\% = 0.85$$

$$\gamma = 1.4$$

$$C_p = 1.024 \text{ kJ/kg}\cdot\text{K}$$

$$\dot{m} = 1065 \text{ kg/s}$$

$$\text{heat supplied} = Q_s / \text{kg of air} = ?$$

$$\eta_{\text{th}} = ?$$

$$m_a = ?$$

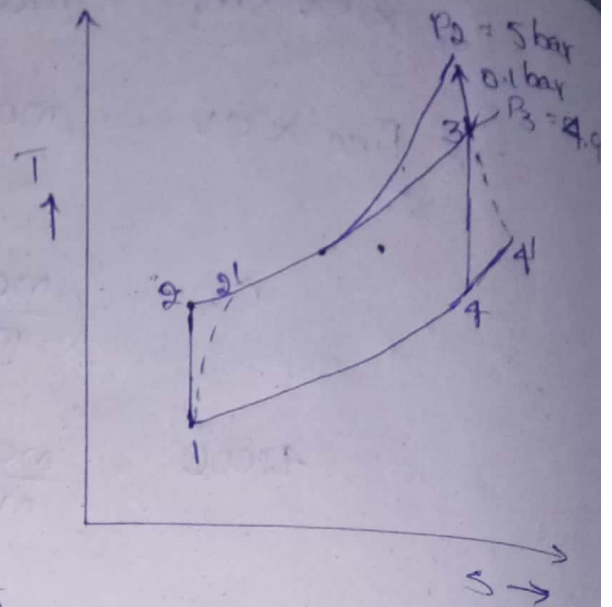
$$(T_2/T_1)^{1/\gamma-1} = (P_2/P_1)^{1/\gamma}$$

$$T_2 = (5)^{1.4-1/1.4} \times 293$$

$$T_2 = 464.05 \text{ K}$$

$$(T_3/T_4)^{1/\gamma-1} = (P_3/P_4)^{1/\gamma}$$

$$\left(\frac{953}{T_4}\right)^{1/1.4-1} = (4.9/1)^{1/1.4}$$



$$T_4 = \frac{953}{1.574}$$

$$T_4 = 605.193 \text{ K}$$

$$\eta_{\text{comp}} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.85 = \frac{464.05 - 293}{T_2' - 293}$$

$$T_2' = 494.23 \text{ K}$$

$$\eta_{\text{turb}} = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$0.8 = \frac{953 - T_4'}{953 - 605.193}$$

$$T_4' = 674.75 \text{ K}$$

$$\begin{aligned} \text{turbine work } w_T &= m c_p (T_3 - T_4') \\ &= 1 \times 1.024 (953 - 674.75) \\ &= 284.92 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} \text{compressor work } w_c &= m c_p (T_2' - T_1) \\ &= 1 \times 1.024 (494.23 - 293) \\ &= 206.05 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} \rightarrow (i) \quad P &= m a \times w_{\text{net}} \\ m a &= P / w_{\text{net}} \end{aligned}$$

$$m_a = \frac{P}{W_T - W_C}$$

$$m_a = \frac{1065}{284.92 - 206.05}$$

$$m_a = 13.504 \text{ kg/s}$$

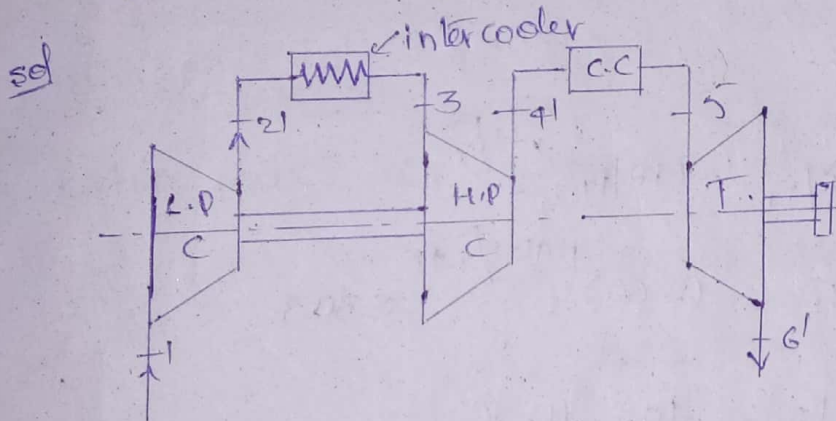
$$\rightarrow 2. \quad \eta_{cc} = \frac{m c_p (T_3 - T_2')}{m_f \times c.v}$$

$$H.S = m_f \times c.v$$

$$\begin{aligned} \text{(heat supplied) } H.S &= \frac{m c_p (T_3 - T_2')}{\eta_{cc}} \\ &= \frac{1 \times 1.024 (953 - 494.23)}{0.85} \\ &= 552.68 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} \rightarrow (c) \quad \eta_{th} &= \frac{W_{net}}{H.S} \times 100 \\ &= \frac{78.87}{552.68} \times 100 \\ &= 14.27 \% \end{aligned}$$

4. The pressure ratio of an open cycle gas turbine power plant 5.6. Air is taken at 30°C & 1 bar. The compression is carried out in two stages with perfect intercooling b/w them. The max temp of the cycle 700°C . Assume isentropic efficiency of the each compression stage is 85% and turbine is 90%. Determine power developed & η of the power plant, if the air flow rate is 1.2 kg/s . mass of the fuel is neglected. Take $C_p = 1.02 \text{ kJ/kg}\cdot\text{K}$, $\gamma = 1.41$.



Given data

$$P_4/P_1 = 5.6$$

$$T_1 = 30 + 273 = 303\text{K} \quad T_1 \uparrow$$

$$P_1 = 1 \text{ bar}$$

$$T_5 = 700 + 273 = 973\text{K}$$

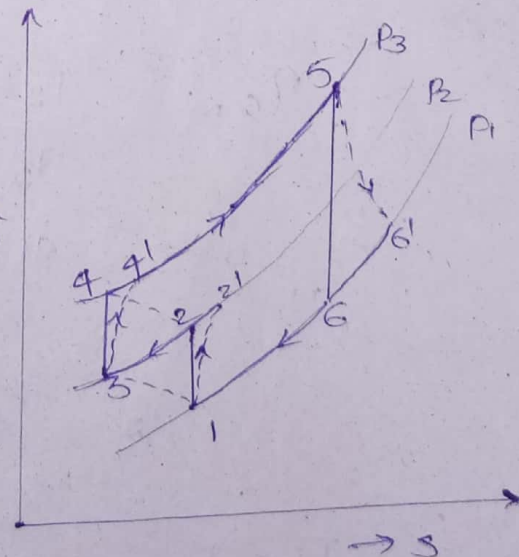
$$\eta_{\text{com}} = 85\% = 0.85$$

$$\eta_{\text{tur}} = 0.9$$

$$m = 1.2 \text{ kg/s}$$

$$C_p = 1.02 \text{ kJ/kg}\cdot\text{K}$$

$$\gamma = 1.41$$



$$T_1 = T_3;$$

$$T_2 = T_4;$$

$$W_{\text{cp1}} = W_{\text{cp2}} \quad \left\{ \begin{array}{l} \text{same} \\ \eta_{\text{com}} = \eta_{\text{comp}} \end{array} \right. \quad (\text{both are})$$

$$\frac{P_4}{P_1} = \frac{P_4}{P_3} \times \frac{P_2}{P_1} \quad \therefore (P_2 = P_3)$$

$$= \frac{P_4}{P_2} \times P_2/P_1$$

$$(\because P_4/P_3 = P_2/P_1)$$

$$P_4/P_1 = (P_2/P_1)^2$$

$$P_2/P_1 = \sqrt{P_4/P_1}$$

$$P_2/P_1 = \sqrt{5.6}$$

$$P_2/P_1 = 2.66$$

(1-2) process :-

$$T_2/T_1 = (P_2/P_1)^{\gamma-1/\gamma}$$

$$T_2 = (2.66)^{1.41-1/1.41} \times 303$$

$$T_2 = 402.70 \text{ K}$$

$$\eta_{\text{com}} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.85 = \frac{402.70 - 303}{T_2' - 303}$$

$$T_2' = 420.30 \text{ K}$$

$$T_1 = T_3 = 303 \text{ K}$$

$$T_2 = T_4 = 402.70 \text{ K}$$

$$T_2' = T_4' = 420.30 \text{ K}$$

(5-6) process : - (at const pressure line) ($P_4/P_1 = P_5/P_6$)

$$T_5/T_6 = (P_5/P_6)^{\gamma-1/\gamma}$$

$$973/T_6 = (5.6)^{1.41-1/1.41}$$

$$T_6 = 589.59 \text{ K}$$

$$\eta_{\text{turb}} = \frac{T_5 - T_6}{T_5 - T_6'}$$

$$0.9 = \frac{973 - T_6'}{973 - 589.59}$$

$$T_6' = 627.936 \text{ K}$$

$$\begin{aligned} \text{turbine work } W_T &= m c_p (T_5 - T_6') \\ &= 1.2 \times 1.02 (973 - 627.30) \\ &= 423.94 \text{ kW} \end{aligned}$$

$$\begin{aligned} \text{compressor work } W_C &= [m c_p (T_2' - T_1)] \times 2 \\ &= [1.2 \times 1.02 (420.30 - 303)] \times 2 \\ &= 287.15 \text{ kW} \end{aligned}$$

$$\begin{aligned} W_{\text{net}} &= W_T - W_C \\ &= 427.13 - 287.15 \\ &= 135.98 \text{ kW} \end{aligned}$$

$$\begin{aligned} \text{Heat supplied } Q_s &= m c_p (T_5 - T_4') \\ &= 1.2 \times 1.02 (973 - 420.30) \\ &= 676.50 \text{ kW} \end{aligned}$$

$$\eta_{th} = \frac{W_{net}}{Q_s} \times 100$$

$$= \frac{135.98}{676.50} \times 100$$

$$= 20.10 \%$$

5. A simple gas turbine cycle works with a pressure ratio of 8. The compressor & turbine inlet temp are 300 K & 800 K. If the volume flow rate of the air is 250 m³/s, calculate power output & thermal efficiency.

Given data :

pressure ratio $P_2/P_1 = 8$

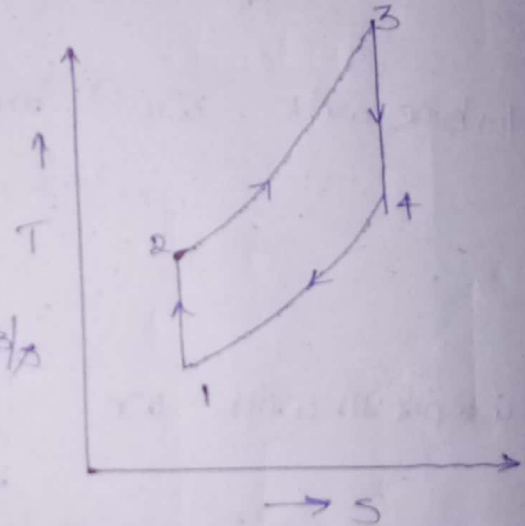
$T_1 = 300 \text{ K}$

$T_3 = 800 \text{ K}$

volume flow rate $V = 250 \text{ m}^3/\text{s}$

$P = ?$

$\eta_{th} = ?$



$$\rightarrow \dot{S} = \dot{m}/V$$

assume $\rho_{air} = 1 \text{ kg/m}^3$

$$\dot{m} = \rho \times V$$

$c_p = 1.005 \text{ kJ/kgK}$

$$= 1 \times 250$$

$\gamma = 1.4$

$$= 250 \text{ kg/s}$$

$\rightarrow$ (1-2) process :-

$$T_2/T_1 = (P_2/P_1)^{\gamma-1/\gamma}$$

$$T_2 = (8)^{1.4-1/1.4} \times 300$$

$$T_2 = 543.43 \text{ K}$$

→ (3-4) Process :

$$T_3/T_4 = (P_3/P_4)^{\gamma-1/\gamma}$$

$$(P_3/P_1 = P_3/P_4)$$

$$\frac{T_3}{T_4} = (P_3/P_1)^{\gamma-1/\gamma}$$

$$T_4 = \frac{800}{(8)^{1.4-1/1.4}}$$

$$T_4 = 441.63 \text{ K}$$

→ power $P = \dot{W}_{\text{net}} \cdot m$

$$P = \dot{m} (\dot{W}_T - \dot{W}_C)$$

$$\dot{W}_T = m c_p (T_3 - T_4)$$

$$= 1 \times 1.005 (800 - 441.63)$$

$$= 360.15 \text{ kJ/kg}$$

$$\dot{W}_C = m c_p (T_2 - T_1)$$

$$= 1 \times 1.005 (543.43 - 300)$$

$$= 244.64 \text{ kJ/kg}$$

$$P = 250 \times (360.15 - 244.64)$$

$$= 28877.5 \text{ kW}$$

$$\begin{aligned} & 1960 \times 10^3 \text{ J/s} \\ & 1960 \times 10^3 \text{ J/s} \\ & 1960 \times 10^3 \text{ J/s} \end{aligned}$$

$$\text{heat supplied } Q_s = m c_p (T_3 - T_2)$$

$$= 1 \times 1.005 (800 - 543.43)$$

$$Q_s = 257.85 \text{ kJ/kg}$$

$$\begin{aligned}\eta_{th} &= \frac{W_{net}}{Q_s} \times 100 \\ &= \frac{115.51}{257.85} \times 100 \\ &= 44.79 \%\end{aligned}$$

6. A constant pressure open cycle gas turbine plant works b/w the range of temp is 15°C & 700°C and pressure ratio of 6. find the mass of air circulating in the installation, if it develop 1100 kW. Also find the heat supplied in the heating chamber.

sol

Given data

$$T_1 = 15 + 273 = 288 \text{ K}$$

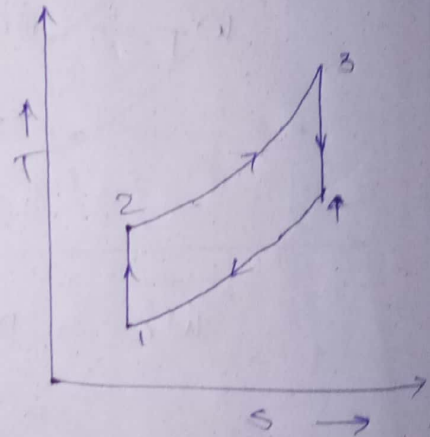
$$T_3 = 700 + 273 = 973 \text{ K}$$

$$\text{pressure ratio } P_2/P_1 = 6$$

$$\text{Power } P = 1100 \text{ kW}$$

$$Q_s = ?$$

$$m_{air} = ?$$



→ (1-2) process

$$T_2/T_1 = (P_2/P_1)^{\gamma-1/\gamma}$$

$$T_2 = (6)^{1.4-1/1.4} \times 288$$

$$T_2 = 480.53 \text{ K}$$

→ (3-4) process :

$$T_3/T_4 = (P_3/P_4)^{\gamma-1/\gamma} \quad (P_3/P_1 = P_4/P_2)$$

$$T_4 = \frac{973}{(6)^{1.4-1/1.4}}$$

$$T_4 = 583.15 \text{ K}$$

$$\begin{aligned} \rightarrow \text{heat supplied } Q_3 &= m c_p (T_3 - T_2) \\ &= 1 \times 1.005 (973 - 480.53) \\ &= 494.93 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} \rightarrow w_c &= m c_p (T_2 - T_1) \\ &= 1 \times 1.005 (480.53 - 288) \\ &= 193.49 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} \rightarrow w_T &= m c_p (T_3 - T_4) \\ &= 1 \times 1.005 (973 - 583.15) \\ &= 391.79 \text{ kJ/kg} \end{aligned}$$

$$\rightarrow \text{power } P = m a w_{\text{net}}$$

$$1100 = m a (w_T - w_c)$$

$$1100 = m a (391.79 - 193.49)$$

$$m a = 5.546 \text{ kg/s}$$

kg/s

7. A gas turbine unit receive the air at 100 kpa & 300 K. It is compressed adiabatically to 620 kpa with efficiency of compressor of 88%. The heating value of the fuel is 44180 kJ/kg & fuel air ratio is 0.017 kg of fuel/kg of air. The turbine internal efficiency is 90%. calculate compressor work, turbine work & thermal η .

Sol

Given data :

$$P_1 = 100 \text{ kpa}$$

$$T_1 = 300 \text{ K}$$

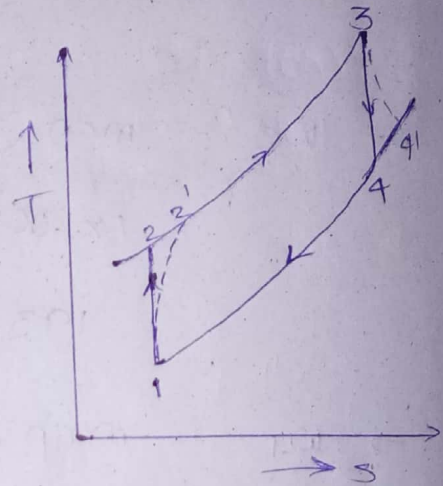
$$P_2 = 620 \text{ kpa}$$

$$\eta_{\text{com}} = 88\% = 0.88$$

$$\text{C.V} = 44180 \text{ kJ/kg}$$

$$\frac{m_f}{m_a} = 0.017 \text{ kg/kg}$$

$$\eta_{\text{turb}} = 90\% = 0.90$$



→ (1-2) process :

$$T_2/T_1 = (P_2/P_1)^{\gamma-1/\gamma}$$

$$T_2 = (620/100)^{1.4-1/1.4} \times 300$$

$$T_2 = 505.26 \text{ K}$$

$$\rightarrow \eta_{\text{com}} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.88 = \frac{505.26 - 300}{T_2' - 300}$$

$$T_2' = 533.25 \text{ K.}$$

$$\rightarrow \eta_{\text{c.c}} = \frac{(m_a + m_f) c_p (T_3 - T_2')}{m_f \times c_v} \quad (\text{if } 100\% \eta_{\text{cc}})$$

$$m_f \times c_v = (m_a + m_f) c_p (T_3 - T_2')$$

divided by m_a

$$\frac{m_f \times c_v}{m_a} = \frac{(m_a + m_f) c_p (T_3 - T_2')}{m_a}$$

$$\frac{m_f}{m_a} \times c_v = \left(1 + \frac{m_f}{m_a}\right) c_p (T_3 - T_2')$$

$$0.017 \times 44180 = (1 + 0.017) \times 1.005 \times (T_3 - 533.25)$$

$$T_3 = 1268.081 \text{ K}$$

$\rightarrow$ (3-4) process

$$T_3/T_4 = (P_3/P_4)^{2-1/2}$$

$$T_3/T_4 = (620/100)^{1.4-1/1.2}$$

$$T_4 = \frac{1268.081}{1.6842}$$

$$T_4 = 752.92 \text{ K}$$

→ compressor work

$$\begin{aligned} w_c &= m c_p (T_2' - T_1) \\ &= 1 \times 1.005 (533.25 - 300) \\ &= 234.41 \text{ kJ/kg} \end{aligned}$$

→ turbine work

$$\begin{aligned} w_T &= m c_p (T_3 - T_4') \\ &= 1 \times 1.005 (1268.081 - 806) \\ &= 465.64 \text{ kJ/kg} \end{aligned}$$

$$\rightarrow \eta_{\text{turb}} = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$0.9 = \frac{1268.081 - T_4'}{1268.081 - 752.92}$$

$$T_4' = 804.43 \text{ K}$$

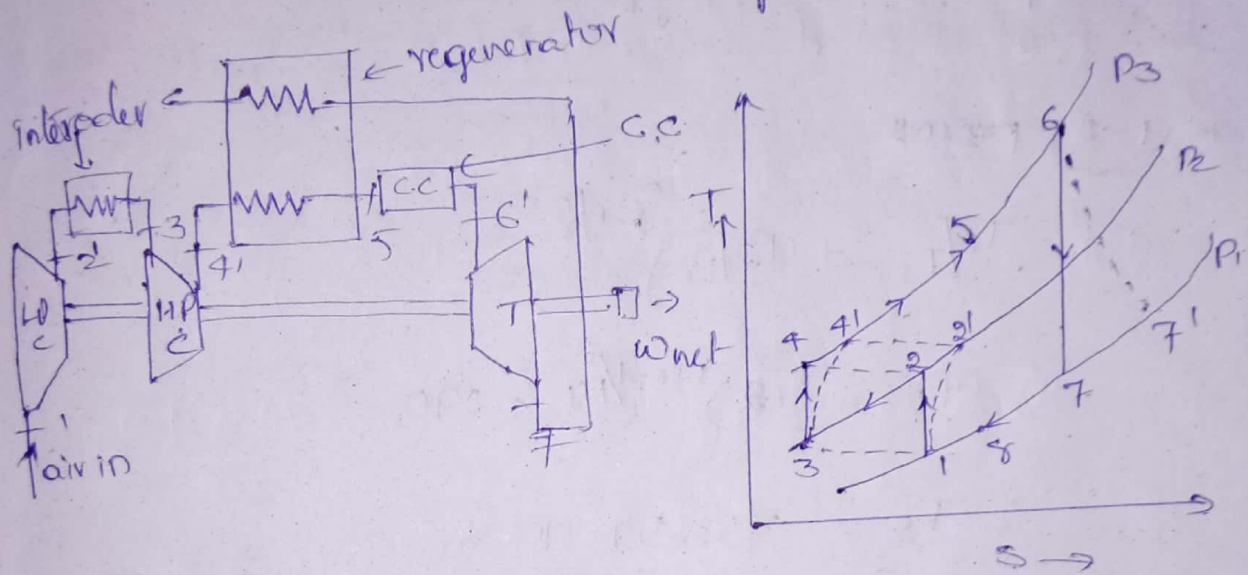
→ heat supplied $Q_s = m c_p (T_3 - T_2')$

$$\begin{aligned} &= 1 \times 1.005 (1268.081 - 533.25) \\ &= 738.505 \text{ kJ/kg} \end{aligned}$$

→ $\eta_{\text{th}} = w_{\text{net}} / Q_s$

$$= \frac{231.55}{738.505} \times 100 = \underline{\underline{31.35\%}}$$

6. Determine the efficiency of a gas turbine plant fitted with a heat-exchanger of 75% effectiveness. The pressure ratio is 4:1 & compressor is carried out in two stages and in equal pressure ratio with intercooling back to initial temp of 290 K. The max temp is 925 K. Turbine isentropic η is 88% and each compressor η is 85% for air $\gamma = 1.4$, $C_p = 1.005 \text{ kJ/kg.K}$



sol $\epsilon = 75\% = 0.75 = \frac{T_5 - T_{41}}{T_{7'} - T_{41}}$

$$P_4/P_1 = 4$$

$$P_4/P_3 = P_2/P_1$$

$$P_4/P_1 = P_4/P_3 \times P_2/P_1$$

$$P_4/P_1 = (P_2/P_1)^2$$

$$P_2/P_1 = \sqrt{P_4/P_1}$$

$$= \sqrt{4} = 2$$

$$T_1 = T_3 = 290 \text{ K}$$

$$T_6 = 925 \text{ K}$$

$$\eta_T = 88\% = 0.88$$

$$\eta_{C_1} = \eta_{C_2} = 85\% = 0.85$$

$$\gamma = 1.4$$

$$C_p = 1.005 \text{ kJ/kg}\cdot\text{K}$$

→ (1-2) process

$$T_2/T_1 = (P_2/P_1)^{\gamma-1/\gamma}$$

$$T_2 = (2)^{1.4-1/1.4} \times 290$$

$$T_2 = 353.51 \text{ K}$$

$$\eta_c = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.85 = \frac{353.51 - 290}{T_2' - 290}$$

$$T_2' = 364.722 \text{ K}$$

→ (3-4) = (1-2) process

$$T_2 = T_4$$

$$T_2' = T_4'$$

→ (6-7) process

$$T_6/T_7 = (P_6/P_7)^{\gamma-1/\gamma}$$

$$T_6/T_7 = (4)^{1.4-1/1.4}$$

$$T_7 = \frac{925}{1.485}$$

$$T_7 = 622.47 \text{ K}$$

$$\rightarrow \eta_{\text{tur}} = \frac{T_6 - T_7'}{T_6 - T_7^*}$$

$$0.88 = \frac{925 - T_7'}{925 - 622.47}$$

$$T_7' = 658.77 \text{ K}$$

$$\rightarrow \epsilon = \frac{T_5 - T_4'}{T_7' - T_4'}$$

$$0.75 = \frac{T_5 - 364.722}{658.77 - 364.722}$$

$$T_5 = 585.27 \text{ K}$$

→ compressor work

$$w_c = (m c_p (T_2' - T_1)) \cdot 2$$

$$= 1 \times 1.005 (364.722 - 290) \cdot 2$$

$$= 150.19 \text{ kJ/kg}$$

→ turbine work

$$\begin{aligned}W_T &= m c_p (T_6 - T_7) \\&= 1 \times 1.005 (925 - 658.77) \\&= 267.56 \text{ kJ/kg}\end{aligned}$$

→ $\eta_{th} = W_{net} / Q_s$

→ heat supplied $Q_s = m c_p (T_6 - T_5)$

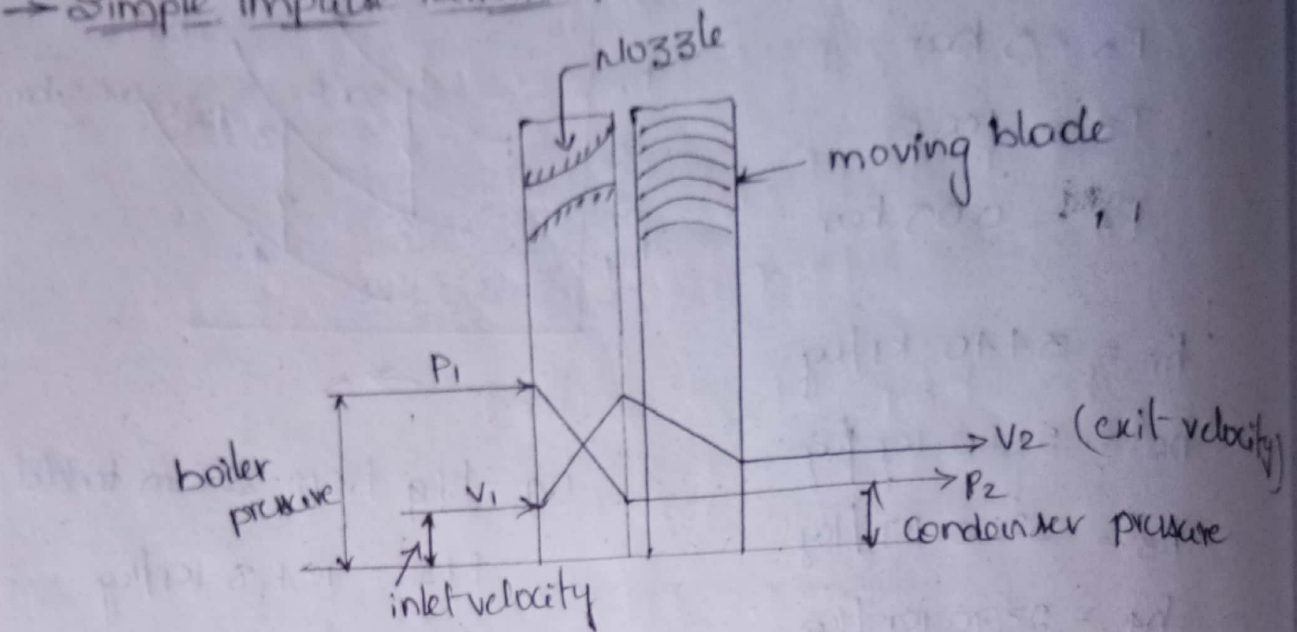
$$\begin{aligned}&= 1 \times 1.005 (925 - 585.27) \\&= 341.42 \text{ kJ/kg}\end{aligned}$$

→ $\eta_{th} = \frac{W_T - W_C}{Q_s} \times 100$

$$\begin{aligned}&= \frac{267.56 - 150.19}{341.42} \times 100 \\&= \underline{\underline{34.37\%}}\end{aligned}$$

3. Impulse turbine

→ Simple impulse turbine :

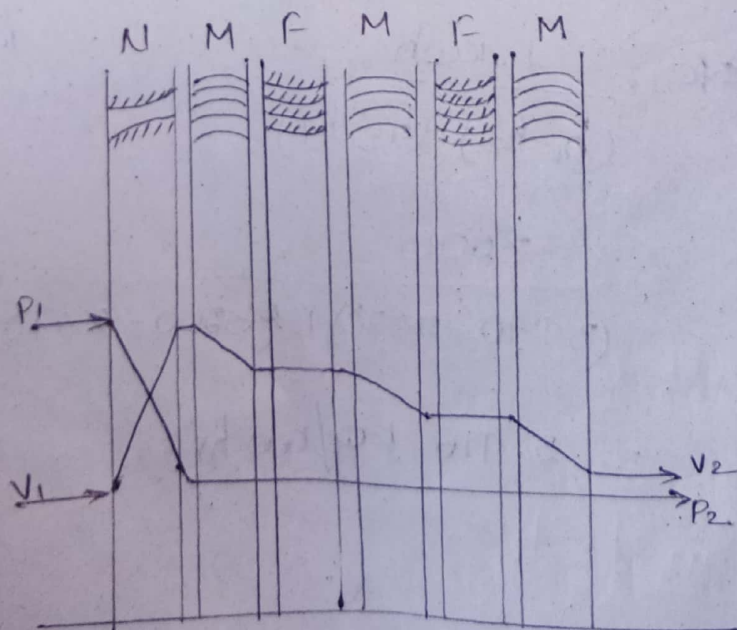


→ Compounding :- Reduce the speed of the rotor by adding external parts to it

* Methods of compounding

- (i) velocity compounding
- (ii) pressure compounding
- (iii) velocity - pressure compounding

(i) velocity compounding :-



N = Nozzle

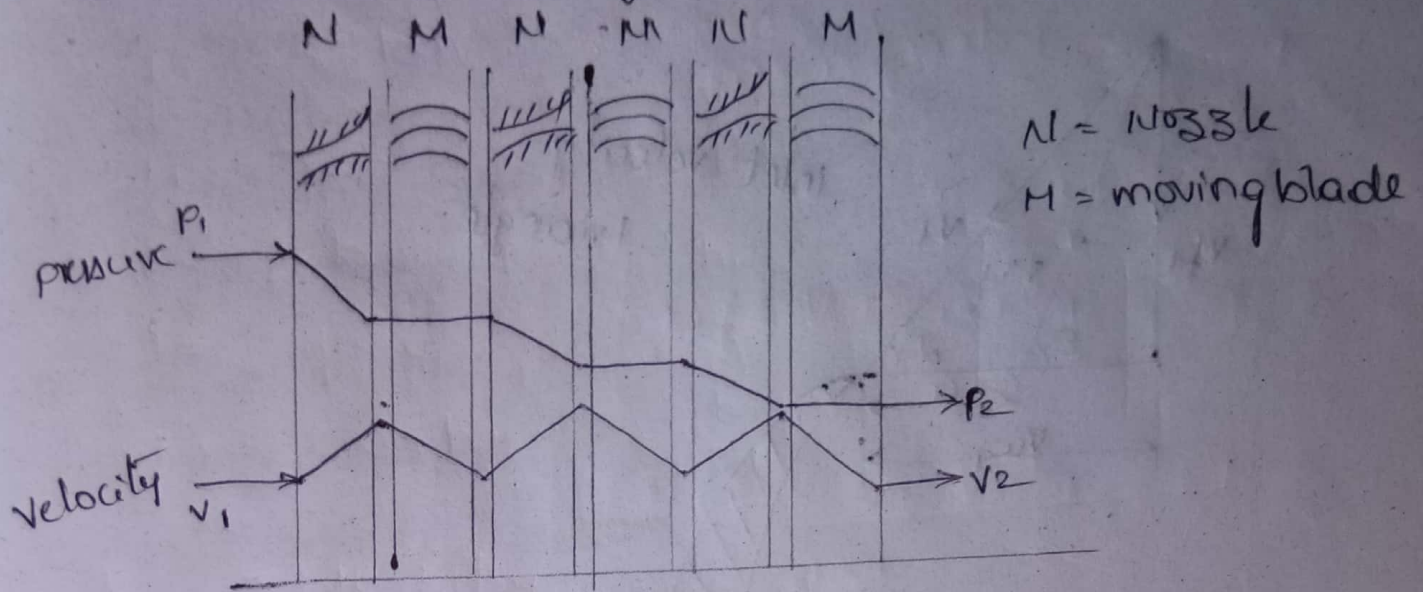
M = moving blades

F = fixed blade

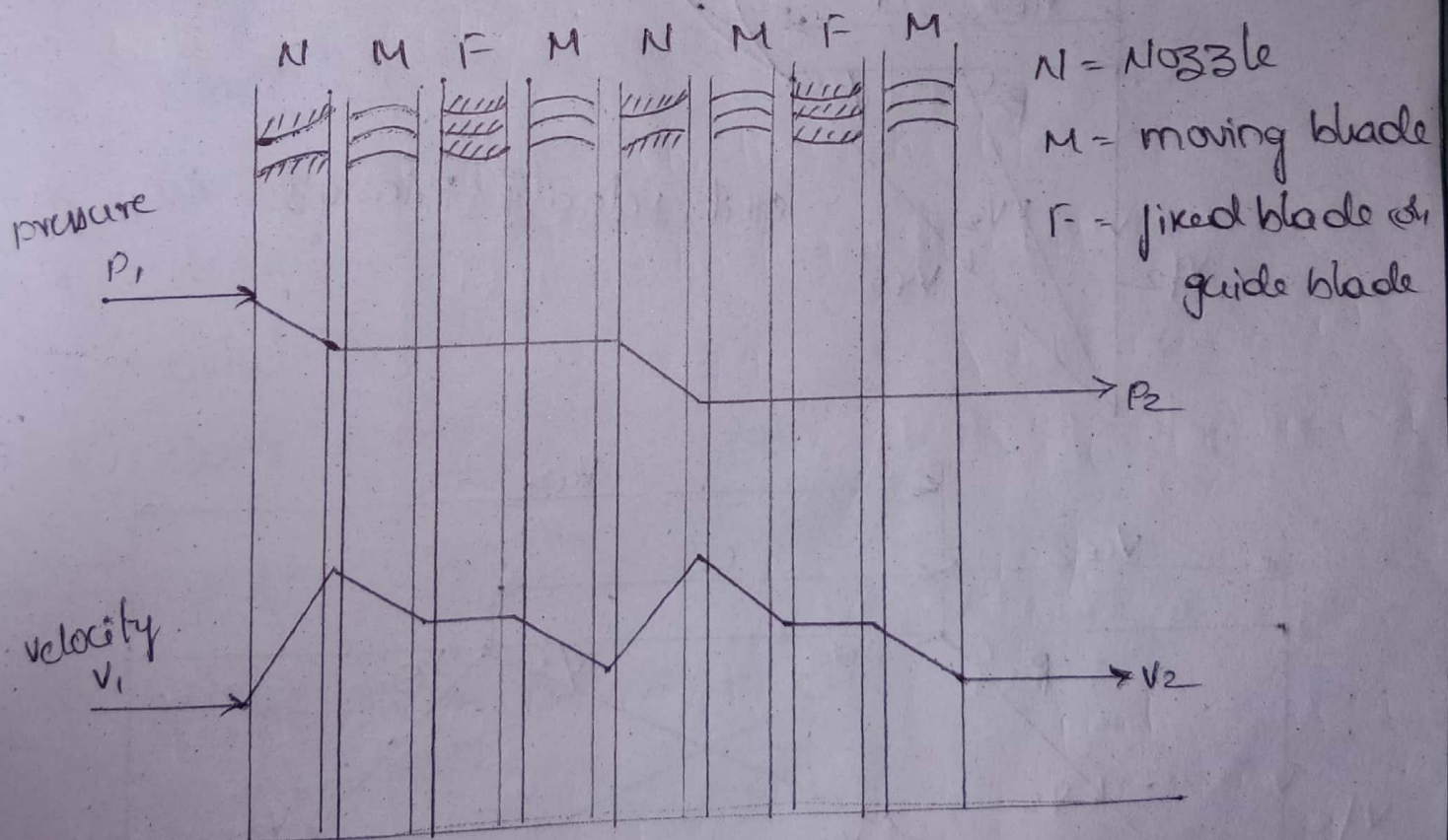
(S)

Guide blade

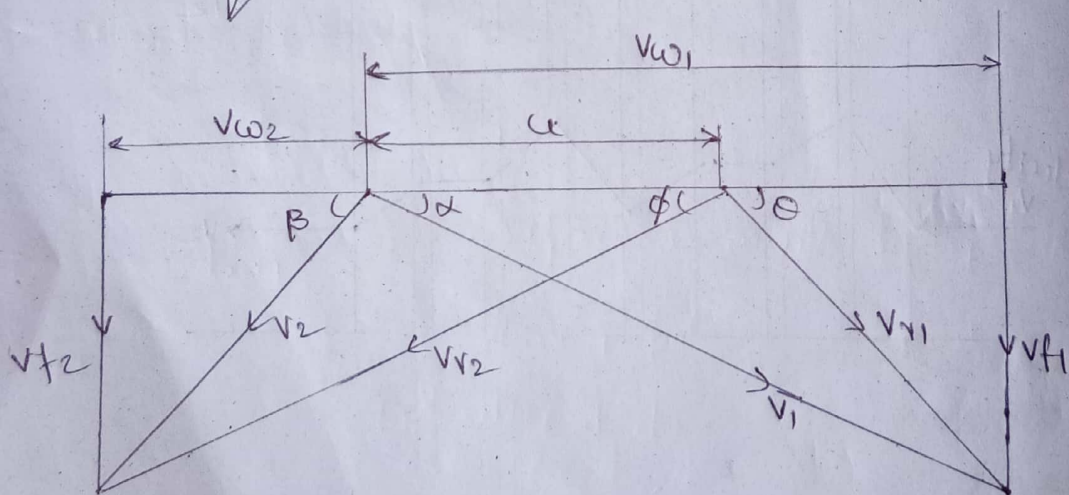
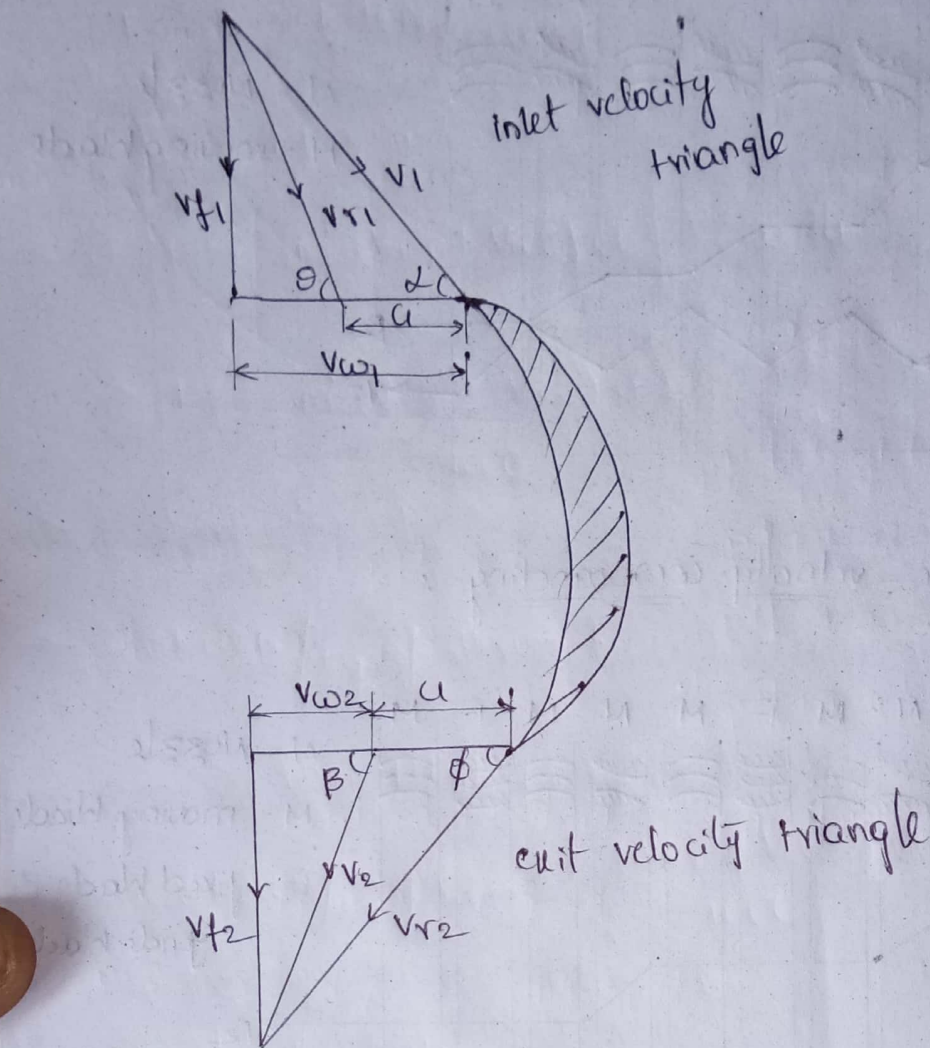
(ii) pressure compounding :-



(iii) pressure-velocity compounding :-



→ combined velocity diagram for impulse turbine



$u \rightarrow$ blade velocity m/s

$v_1 \rightarrow$ inlet steam velocity at blade inlet m/s

$v_{fi} \rightarrow$ flow velocity at inlet m/s

$v_{wi} \rightarrow$ whirl velocity at inlet m/s

$v_{we} \rightarrow$ whirl velocity at exit m/s

$v_{fe} \rightarrow$ flow velocity at exit m/s

$\alpha \rightarrow$ Nozzle angle

$\theta \rightarrow$ moving blade inlet angle

$\beta \rightarrow$ discharge angle

$\phi \rightarrow$ moving blade outlet angle

Important Terms :-

a. Tangential force (F_T)

b. power developed

c. work done / kg of steam

d. Nozzle efficiency

e. Blade / diagram efficiency

f. stage efficiency

g. Blade velocity ω -efficient

h. loss due to friction

i. driving force on wheel

J. axial thrust

k. blade speed ratio

$\rightarrow$ Tangential force (F_T) :-

$$F_T = m \times a$$

$$F_T = m \times [V_{w1} \pm V_{w2}]$$

$$F_T = \frac{\text{kg}}{\text{s}} \times \frac{\text{m}}{\text{s}} = \frac{\text{kg-m}}{\text{s}^2} = \text{N}$$

+ve sign $\rightarrow$ when V_{w1} & V_{w2} are in

-ve sign $\rightarrow$ when V_{w1} & V_{w2} are in

→ Power developed :-

$$P = \text{work done / second}$$

$$P = F_t \times u$$

$$P = m (V_{w1} \pm V_{w2}) u$$

watts

$$\Rightarrow P = \frac{m (V_{w1} \pm V_{w2}) u}{1000}$$

kW

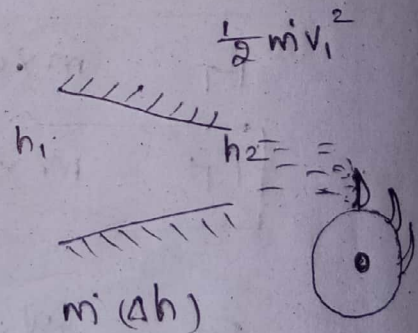
→ work done / kg of steam :-

$$\text{if } m = 1 \text{ kg/s}$$

$$\Rightarrow \text{work done / kg of steam} = \frac{(V_{w1} \pm V_{w2}) u}{1000} \text{ kW}$$

→ Nozzle efficiency :-

$$\Rightarrow P = \frac{m (V_{w1} \pm V_{w2}) u}{1000} \text{ kW}$$



$$\eta_N = \frac{\text{K.E of steam at exit of nozzle}}{\text{enthalpy drop in nozzle}}$$

$$\eta_N = \frac{\frac{1}{2} m v_1^2}{m(\Delta h)} \times 100$$

$$\Rightarrow \eta_N = \frac{v_1^2}{2(\Delta h)} \times 100$$

→ Blade or diagram efficiency :-

$$\eta_H = \frac{\text{work done on blade}}{\text{K.E of steam at inlet to turbine}}$$

$$= \frac{\dot{m} (V_{w1} \pm V_{w2}) u}{\frac{1}{2} \dot{m} V_1^2}$$

$$\Rightarrow \eta_{bl} = \frac{2u (V_{w1} \pm V_{w2})}{V_1^2} \times 100$$

→ stage efficiency :-

$$\eta_s = \frac{\text{work done on blade}}{\text{enthalpy drop in nozzle}}$$

$$= \frac{\dot{m} (V_{w1} \pm V_{w2}) u}{\dot{m} (\Delta h)} \times 100$$

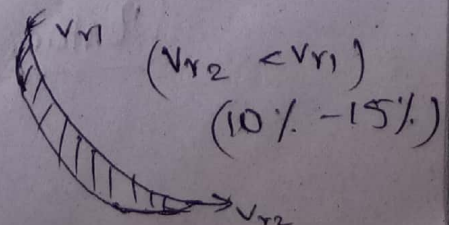
$$\Rightarrow \eta_s = \frac{(V_{w1} \pm V_{w2}) u}{(\Delta h)} \times 100 \quad (\%)$$

$$\Rightarrow \eta_{\text{stage}} = \eta_{\text{nozzle}} \times \eta_{\text{blade}}$$

→ Blade velocity co-efficiency / coefficient of velocity /
friction factor (K)

$$K = \frac{\text{relative velocity of steam at exit}}{\text{relative velocity of steam at entry}}$$

$$\Rightarrow K = \frac{V_{r2}}{V_{r1}}$$



→ loss due to friction :-

$$\Rightarrow \frac{V_{r1}^2 - V_{r2}^2}{2000} \text{ kJ}$$

→ driving force on wheel :-

$$\Rightarrow F_T = \dot{m} (V_{w1} \pm V_{w2}) \quad \text{N.}$$

→ axial thrust :-

$$F_a = \dot{m} \times \text{axial acceleration}$$

$$\Rightarrow F_a = \dot{m} (V_{f1} - V_{f2}) \quad \text{N.}$$

$$\text{if } V_{f1} = V_{f2}$$

$$\Rightarrow F_a = \dot{m} (0) = \underline{0}$$

→ blade speed ratio :-

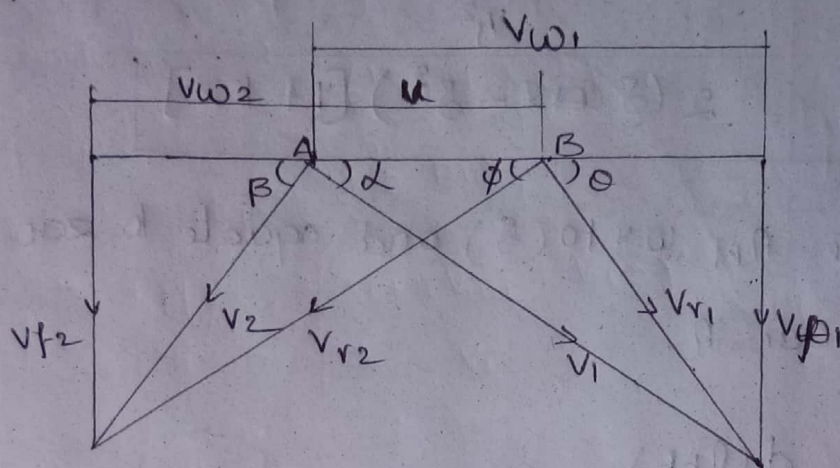
$$\delta = \frac{\text{Blade speed}}{\text{Steam speed}}$$

$$\Rightarrow \delta = \frac{u}{V_1}$$

Note :- if friction losses are neglected then

$$\boxed{\eta_{\text{stage}} = \eta_{\text{blade}}}$$

* * * Expression for optimum value of blade speed to the steam speed (for max η condition) for single stage impulse turbine :-



$$V_w = V_{r1} \cos \theta + V_{r2} \cos \phi$$

$$V_w = V_{r1} \cos \theta \left[1 + \frac{V_{r2} \cos \phi}{V_{r1} \cos \theta} \right]$$

Note : Assume ^{no} friction force in moving blade.

$K = (V_{r1} = V_{r2})$

$K = 1$

for impulse turbine, assume blade is symmetrical

$Z = \frac{\cos \phi}{\cos \theta} \quad (\theta = \phi)$

$Z = 1.$

$$V_w = V_{r1} \cos \theta (1 + KZ)$$

$$V_w = (V_1 \cos \alpha - u) (1 + KZ)$$

from blade η

$$\eta_{bl} = \frac{2u(V_w)}{V_1^2}$$

$$\eta_{bl} = \frac{2u(V_1 \cos \alpha - u)(1+kz)}{V_1^2}$$

$$\eta_{bl} = \frac{2(uv_1 \cos \alpha - u^2)(1+kz)}{V_1^2}$$

$$\boxed{\eta_{bl} = 2(\delta \cos \alpha - \delta^2)(1+kz)}$$

differentiate η_{bl} w.r.to (δ) and equate to zero for max blade η .

$$\frac{d(\eta_{bl})}{d\delta} = 0$$

$$\Rightarrow 2(\cos \alpha - 2\delta)(1+kz) = 0$$

$$\Rightarrow \cos \alpha - 2\delta = 0$$

$$\Rightarrow \cos \alpha = 2\delta$$

$$\boxed{\delta = \frac{\cos \alpha}{2}} \rightarrow \text{for optimum}$$

$$\eta_{bl} = 2\delta(\cos \alpha - \delta)(1+kz)$$

$$= 2 \times \frac{\cos \alpha}{2} \left(\cos \alpha - \frac{\cos \alpha}{2} \right) (1+kz)$$

$$= \cos \alpha \left(\frac{2\cos \alpha - \cos \alpha}{2} \right) (1+kz)$$

$$= \cos \alpha \left(\frac{\cos \alpha}{2} \right) (1+kz) \quad \left\{ \begin{array}{l} k=1 \\ z=1 \end{array} \right.$$

$$= \cos \alpha \left(\frac{\cos \alpha}{2} \right) (1+1)$$

$$= \cos \alpha \left(\frac{\cos \alpha}{2} \right) 2$$

$$\boxed{\eta_{bl} = \cos^2 \alpha} \rightarrow \text{for max blade } \eta$$

Assume $\alpha = 20^\circ$ for impulse turbine

$$\eta_{bl} = \cos^2(20^\circ)$$

$$= 0.883 \times 100$$

$$= \underline{88.3\%} \rightarrow \text{in theoretical}$$

$$\eta_{bl} = \underline{55\%} \rightarrow \text{for actual.}$$

Work done/kg of steam is given by :

$$W = F_T \times u$$

$$W = m (V_{w1} \pm V_{w2}) \times u$$

$$\therefore [m = 1 \text{ kg/s} \quad \& \quad V_w = V_{w1} \pm V_{w2}]$$

$$W = V_w \times u$$

$$W = (V_1 \cos \alpha - u) [1 + kZ] \times u \quad \left\{ \begin{array}{l} k=1 \\ Z=1 \end{array} \right.$$

$$W = (V_1 \cos \alpha - u) 2u$$

$$W = (V_1 2\delta - u) 2u$$

$$W = \left(V_1 \times 2 \times \frac{u}{V_1} - u \right) 2u$$

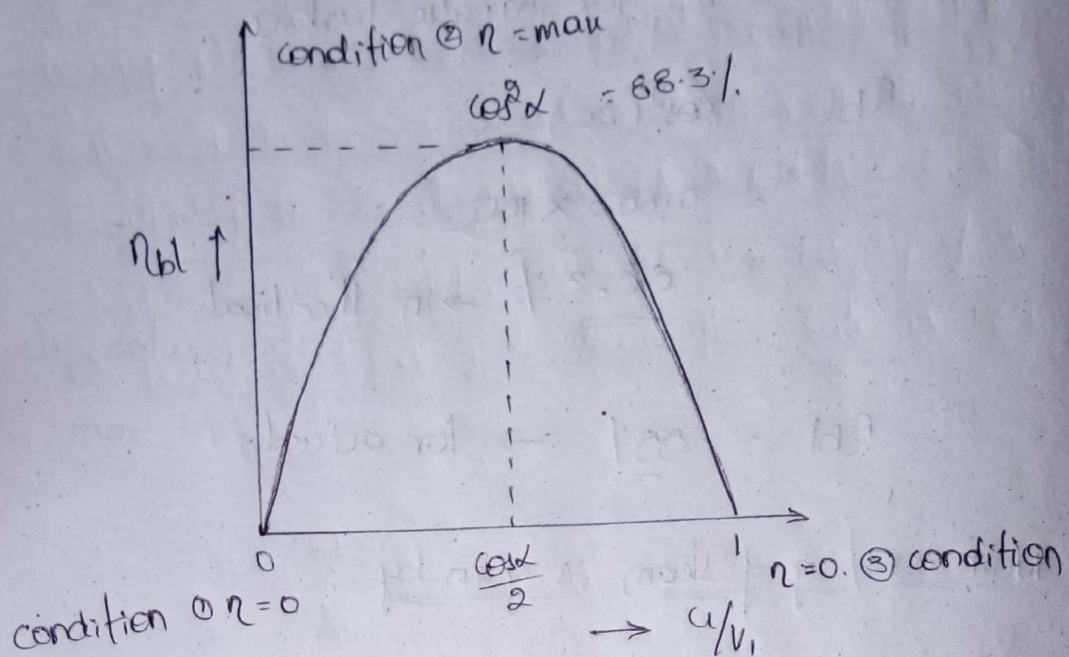
$$W = 2u (2u - u)$$

$$W = 2u (u)$$

$$\boxed{W_{\max} = 2u^2}$$

$$\left\{ \begin{array}{l} \sin \alpha = \frac{u}{V_1} \\ \cos \alpha = \frac{V_1 \times 2}{V_1} \end{array} \right.$$

* Variation of blade efficiency with blade steam ratio



$$S = u/v_1$$

$$(\alpha = 20^\circ)$$

$$\frac{\cos \alpha}{2} = u/v_1$$

$$\frac{\cos 20^\circ}{2} = u/v_1$$

$$u/v_1 = \frac{1}{2} \Rightarrow \boxed{u = \frac{1}{2} v_1}$$

① In a single stage impulse turbine the blade angles are equal & nozzle angle is 20° . The velocity coefficient for the blade is 0.83. Find the max blade efficiency possible. If the actual blade efficiency is 90% of max blade efficiency (η_{bl}). Find the possible ratio of blade speed to the steam blade speed.

sol

Given data

$$\alpha = 20^\circ$$

velocity coefficient of blade $k = 0.83$

blade angle $\theta = \phi$

actual $\eta_{\text{blade}} = 90\% = 0.90$ max η_{blade}

$$\frac{a}{V_1} = \delta = ?$$

$$\begin{aligned} [\eta_{\text{blade}}]_{\text{max}} &= \left(\frac{\cos^2 \alpha}{2} \right) [1 + kZ] \\ &= \left(\frac{\cos^2 20^\circ}{2} \right) [1 + 0.83(1)] \\ &= 80.7\% \end{aligned}$$

$$\begin{aligned} [\eta_{\text{blade}}]_{\text{actual}} &= (0.90 \times 0.80) \times 100 \\ &= 72\% \end{aligned}$$

$$(\eta_{\text{blade}})_{\text{actual}} = 2[\delta \cos \alpha - \delta^2] (1 + kZ)$$

$$0.727 = 2(\delta \cos 20^\circ - \delta^2) [1 + 0.83(1)]$$

$$0.727 = 2[\delta \cdot 0.939 - \delta^2] [1.83]$$

$$0.727 = (0.939\delta - \delta^2) 3.66$$

$$\delta^2 - 0.939\delta + 0.1986 = 0$$

$$\boxed{\delta = 0.6172}$$

1. steam enters a impulse wheel having a nozzle angle of 20° at a velocity of 450 m/s . The exit angle of the moving blade is 20° and relative velocity of the steam assumed to be remains constant over the moving blade. If the blade speed is 180 m/s . calculate blade angle at inlet. B) wBk done per kg of steam c). power developed if the steam flow rate is 1.6 kg/sec

sol Given data

$$V_1 = 450 \text{ m/s}$$

$$\alpha = 20^\circ$$

$$\phi = 20^\circ$$

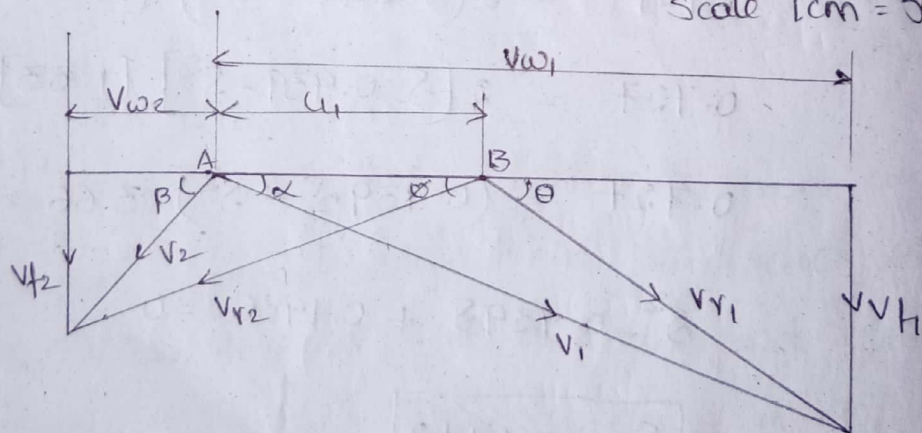
$$u = 180 \text{ m/s}$$

$$V_{r1} = V_{r2} ; K=1$$

$$\theta = ? ; w/p = ? ; P = ?$$

$$m = 1.6 \text{ kg/sec}$$

$$\text{Scale } 1 \text{ cm} = 50 \text{ m/s}$$



$$V_1 = 9 \text{ cm} = 450 \text{ m/s}$$

$$V_{r1} = 5.8 \text{ cm} = 290 \text{ m/s}$$

$$V_{r2} = 5.8 \text{ cm} = 290 \text{ m/s}$$

$$V_2 = 2.8 \text{ cm} = 140 \text{ m/s}$$

$$\theta = 32^\circ$$

$$\alpha = 20^\circ$$

$$\phi = 20^\circ$$

$$\beta = 47^\circ$$

$$u_1 = 3.6 \text{ cm} = \cancel{3600} \text{ m/s} \quad 180 \text{ m/s}$$

$$v_{w1} = 8.3 \text{ cm} = \cancel{8300} \cdot 425 \text{ m/s}$$

$$v_{w2} = 1.9 \text{ cm} = \cancel{1900} \quad 95 \text{ m/s}$$

(i) blade angle at inlet

$$\theta = \underline{32^\circ}$$

(ii) work done per kg of steam

$$\text{w.p./kg} = \frac{m' (v_{w1} + v_{w2}) u}{1000}$$

$$v_{w1} = 8.3 \times 50 = 425 \text{ m/s}$$

$$v_{w2} = 1.9 \times 50 = 95 \text{ m/s}$$

$$\begin{aligned} \text{w.p./kg} &= \frac{1 (425 + 95) \cdot 180}{1000} \\ &= 93.6 \text{ kJ/kg} \end{aligned}$$

(iii) Power $P = \frac{m' (v_{w1} + v_{w2}) u}{1000}$

$$P = \frac{1.6 (425 + 95) \cdot 180}{1000}$$

$$P = 149.76 \text{ kW}$$

2. In a single stage impulse turbine, the steam jet from the nozzle at 20° to the plane of wheel at a speed of 670 m/s and it enters the moving blades at an angle of 35° to the drum axis. The moving blades are symmetrical in shape. Determine the blade velocity & diagram efficiency.

3d Given data

$$V_1 = 670 \text{ m/s}$$

$$\beta = 20^\circ$$

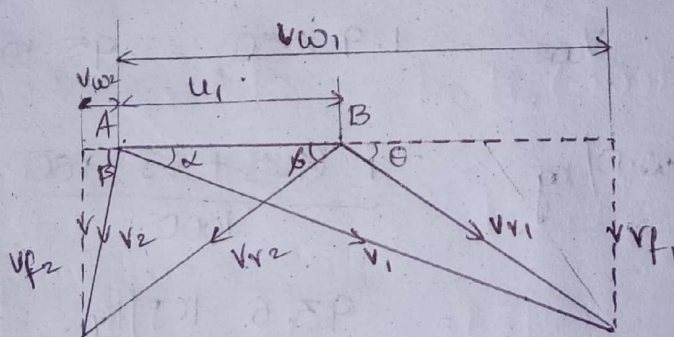
$$\theta = 35^\circ$$

$$\theta = \phi$$

$$u = ?$$

$$\eta_{\text{diag}} = ?$$

$$\text{scale } 1 \text{ cm} = 100 \text{ m/s}$$



$$u_1 = 2.9 \text{ cm} = 290 \text{ m/s}$$

$$V_1 = 6.7 \text{ cm} = 670 \text{ m/s}$$

$$V_{r1} = 4.1 \text{ cm} = 410 \text{ m/s}$$

$$V_{r2} = 4.1 \text{ cm} = 410 \text{ m/s}$$

$$V_2 = 2.4 \text{ cm} = 240 \text{ m/s}$$

$$V_{w1} = 6.3 \text{ cm} = 630 \text{ m/s}$$

$$V_{w2} = 0.5 \text{ cm} = 50 \text{ m/s}$$

(i) blade velocity

$$u = 2.9 \text{ cm} \times 100$$

$$\therefore u = \underline{290 \text{ m/s}}$$

(ii) diagram efficiency

$$\begin{aligned} \eta_{bl} &= \frac{2u (V_{w1} + V_{w2})}{V_1^2} \times 100 \\ &= \frac{2 \times 290 (630 + 50)}{670^2} \times 100 \\ &= \frac{394400}{448900} \times 100 \\ &= \underline{87.8 \%} \end{aligned}$$

3. Steam leaves the nozzle of a single stage impulse turbine at 840 m/s. The nozzle angle is 18° and the blade angles are 29° at the inlet and outlet. The friction coefficient is 0.9. Calculate (i) blade velocity (ii) Steam mass flow rate in kg/hr to develop 300 kW power

sol

Given data

$$V_1 = 840 \text{ m/s}$$

$$\alpha = 18^\circ$$

$$\theta = 29^\circ$$

$$\phi = 29^\circ$$

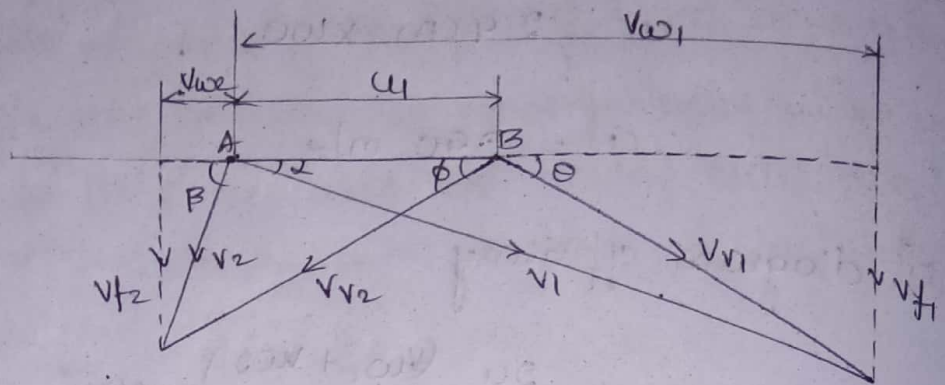
$$k = 0.9$$

$$V_{r1} = k V_{r2}$$

$$P = 300 \text{ kW}$$

$$= 300 \times 10^3 \text{ W}$$

Scale 1 cm = 100 m/s



$$V_1 = 8.4 \text{ cm} = 840 \text{ m/s}$$

$$V_2 = 2.5 \text{ cm} = 250 \text{ m/s}$$

$$V_{v1} = 5.3 \text{ cm} = 530 \text{ m/s}$$

$$V_{v2} = 4.8 \text{ cm} = 480 \text{ m/s}$$

$$\alpha = 18^\circ$$

$$\theta = 29^\circ \text{ \& } \phi = 29^\circ$$

(i) blade velocity

$$U_1 = 3.3 \times 100$$

$$U_1 = 330 \text{ m/s}$$

(ii) Steam mass flow in kg/hr

$$P = \frac{m' (V_{w1} + V_{w2})}{1000} \times U$$

$$300 \times 10^3 = \frac{m' (800 + 90)}{1000} \times 330$$

$$m' = 1021145 \text{ kg/sec}$$

$$m' = 3677.22 \text{ kg/hr}$$

4. A single row impulse turbine develops 132.4 kW at a blade speed of 175 m/sec using 2 kg of steam/sec. Steam leaves the nozzle at 400 m/sec. Velocity coefficient of the blades is 0.9. Steam leaves the turbine blades axially. Determine nozzle angle, blade angles at entry and exit. Assume no shock.

sol Given data

$$P = 132.4 \text{ kW}$$

$$u = 175 \text{ m/sec} = 3.5 \text{ m/s}$$

$$V = 400 \text{ m/s} = 8 \text{ m/s}$$

$$m = 2 \text{ kg}$$

$$K = 0.9$$

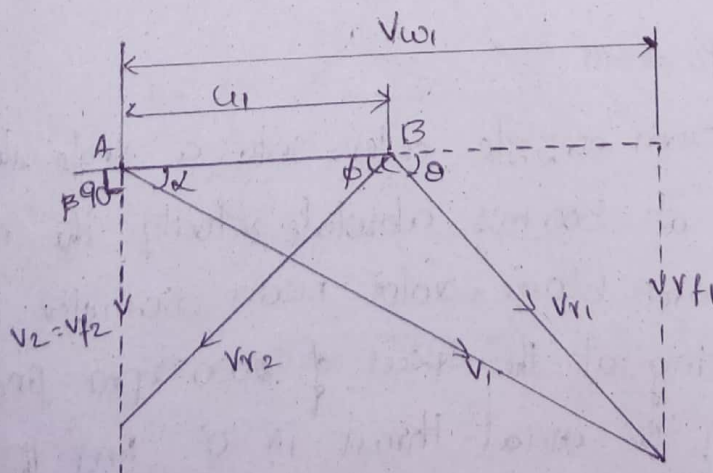
$$\theta, \phi, \beta, \alpha = ?$$

$$\delta = u/V$$

$$= 175/400 = 0.437$$

$$\delta = \frac{\cos \alpha}{2} \Rightarrow \alpha = \frac{2\delta}{\cos} = \alpha = \underline{\underline{28.95^\circ}}$$

Scale 1 cm = 200 m



$$\theta = 48^\circ$$

$$\phi = 42^\circ$$

$$\alpha = 28.95^\circ$$

$$\beta = 90^\circ$$

3)

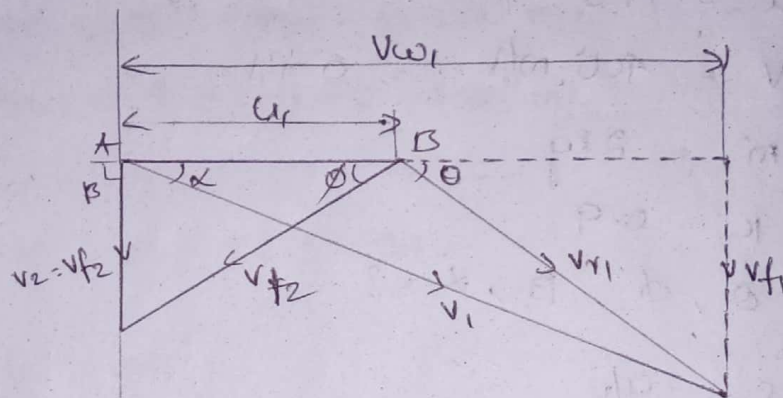
$$P = \frac{m (V_{w1} + V_{w2}) u}{1000}$$

$$132.4 = \frac{2 (V_{w1} + 0) u}{1000}$$

$$V_{w1} = 378.4 \text{ m/s}$$

$$V_{w1} = 7.5 \text{ cm}$$

$$\text{scale } 1 \text{ cm} = 50 \text{ m/s}$$



$$\alpha = 20.5^\circ$$

$$\theta = 36^\circ$$

$$\phi = 31^\circ$$

$$\beta = 90^\circ$$

- 5) steam from nozzle enters into a single stage impulse turbine at 300 m/s absolute velocity the nozzle angle is 25° and blade root mean diameter is 100 cm is rotating at the speed of 2000 rpm find the blade angles if the axial thrust is 0. find the power developed when the steam flow rate is 600 kg/min. Take blade velocity coefficient 0.9.

3d Given data

$$\alpha = 25^\circ$$

$$V_1 = 300 \text{ m/s}$$

$$d = 100 \text{ cm}$$

$$N = 2000 \text{ rpm}$$

$$\theta \text{ \& } \phi = ?$$

$$\text{axial thrust} = 0. \quad (V_{f1} = V_{f2})$$

$$\dot{m} = 600 \text{ kg/min} = 600/60 = 10 \text{ kg/sec}$$

$$K = 0.9$$

$$V_{f2} = 0.9 \times V_{f1}$$

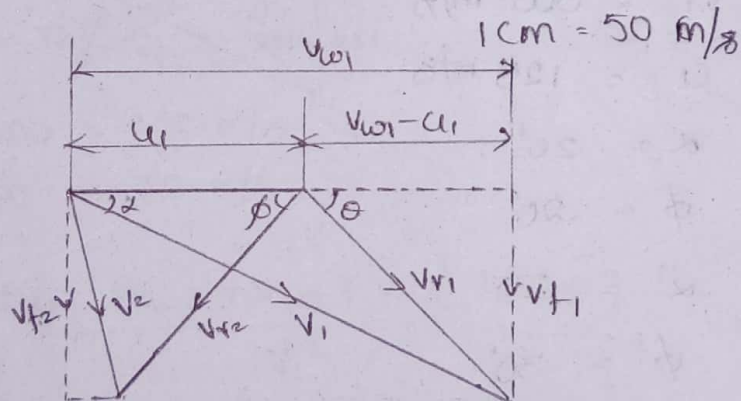
$$u_1 = \frac{\pi d N}{60}$$

$$= \frac{100}{100} \pi \times 2000/60$$

$$= 1 \times \pi \times 2000/60$$

$$= 104.71 \text{ m/s}$$

$$V_{f2} = 3.24$$



$$\theta = 45^\circ$$

$$\phi = 49^\circ$$

$$V_{w1} = 5.4 \times 50 = 270 \text{ m/s}$$

$$V_{w2} = 0$$

$$P = \frac{\dot{m} (V_{w1} - V_{w2}) u}{1000}$$

$$= \frac{10(270 - 0) \times 104.71}{1000}$$

$$= 391.5 \text{ kW}$$

* problems on compound impulse turbine :

1. The following data relate to a compound impulse turbine having two rows of moving blades and one row of fixed blade in between them.

a. velocity of the leaving the nozzle = 600 m/s

b. blade speed = 125 m/s

c. Nozzle angle $\alpha = 20^\circ$

d. first moving blade discharge angle = 20°

e. first fixed blade discharge angle = 25°

f. second moving blade discharge angle = 30°

g. friction loss in each ~~row~~ ring = 10% of relative velocity

find diagram η & power developed for a steam flow of 6 kg/sec.

sol

Given data

$$V_1 = 600 \text{ m/s}$$

$$u = 125 \text{ m/s}$$

$$\alpha = 20^\circ$$

$$\phi = 20^\circ$$

$$\alpha' = 25^\circ$$

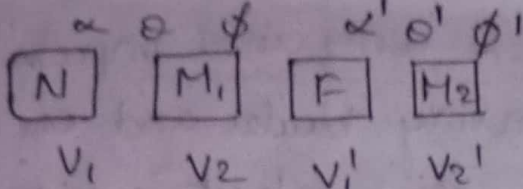
$$\phi' = 30^\circ$$

$$k = 0.9$$

$$\dot{m} = 6 \text{ kg/s}$$

$$\eta_{\text{blade}} = ?$$

$$P = ?$$

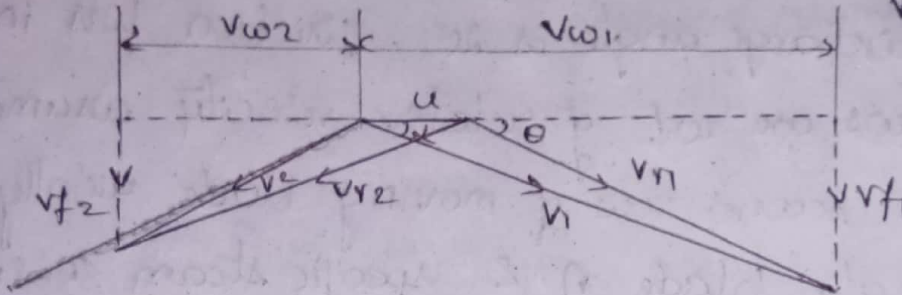


$$K = \frac{V_{y2}}{V_{y1}} = 0.9$$

$$K = \frac{V_{y2'}}{V_{y1'}} = 0.9$$

$$K = \frac{V_{x1'}}{V_{x2}} = 0.9$$

Scale 1cm = 100 m/s

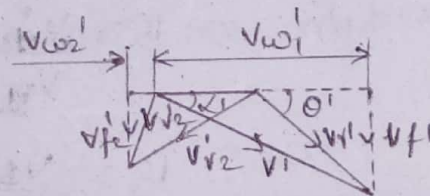


$$V_{x1} = 4.9 \times 100 = 490 \text{ (m/s)} \quad \text{first row of moving blade}$$

$$V_{x2} = 4.41 \times 100 = 441 \text{ (m/s)}$$

$$V_{w1} = 5.7 \times 100 = 570 \text{ (m/s)}$$

$$V_{w2} = 2.8 \times 100 = 280 \text{ (m/s)}$$



$$\frac{V_{x1'}}{V_{x2}} = 0.9$$

$$V_{x1} = -\checkmark$$

$$V_{w1} = 2.6 \times 100 = 260 \text{ m/s}$$

$$V_{w2} = 0.3 \times 100 = 30 \text{ m/s}$$

$$\begin{aligned} \rightarrow \eta_{\text{blade}} &= \frac{2u (V_{w1} + V_{w2} + V_{w1'} + V_{w2'})}{V_1^2} \\ &= \frac{2 \times 125 (570 + 280 + 260 + 30)}{(600)^2} = 79.16\% \end{aligned}$$

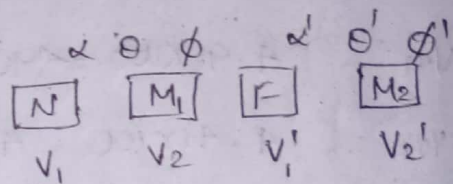
$$\begin{aligned} \rightarrow \text{power } P &= \frac{m' (V_{w1} + V_{w2} + V_{w1'} + V_{w2'}) u}{1000} \\ &= \frac{6 (570 + 280 + 260 + 30) 125}{1000} \end{aligned}$$

$$P = 855 \text{ kW}$$

2. the following data relate to a compound impulse turbine having 2 rows of moving blades and one row of fixed blade in b/w them. steam velocity coming out of the nozzle 450 m/s, nozzle angle 15° , moving blade tip discharge angles are 30° , fixed blade discharge angle is 20° , friction loss in each blade rows are 10% of relative velocity assume steam leaves the second row of moving blade axially. find blade velocity, blade η & specific steam consumption

sol the turbine

Given data



$$V_1 = 450 \text{ m/s}$$

$$\alpha = 15^\circ$$

$$\phi = \phi' = 30^\circ$$

$$\alpha' = 20^\circ$$

$$\theta' = 90^\circ$$

$$\eta = 0.9$$

$$\eta = \frac{V_{r2}}{V_{r1}} = 0.9$$

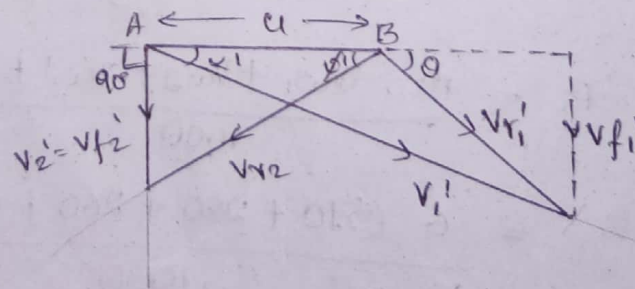
$$\eta = \frac{V_{r1}}{V_{r2}} = 0.9$$

$$\eta = \frac{V_{r1}}{V_{r2}} = 0.9$$

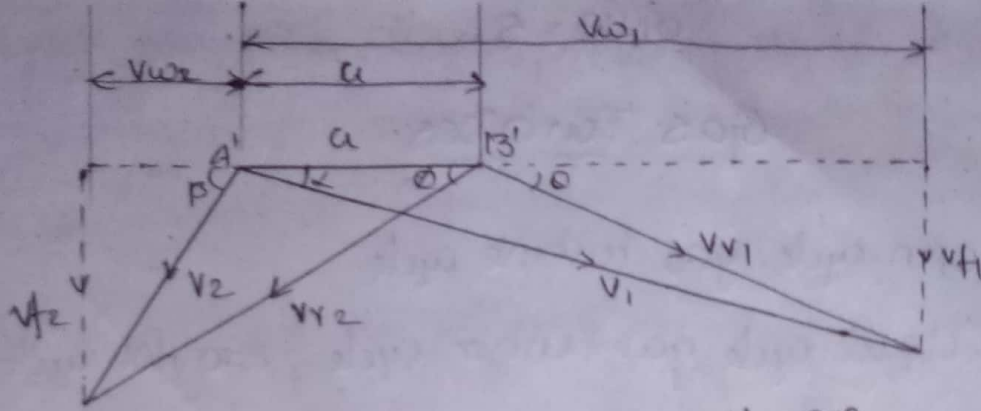
$$\text{take } u = 30 \text{ m/s}$$

Scale

$$1 \text{ cm} = 50 \text{ m/s}$$



second row of moving velocity diagram



first row of moving diagram

$$V_{v2}/V_{v1} = 0.9$$

$$V_{v2} = V_{v1} \times 0.9$$

$$V_{v2} =$$

$$\eta_{\text{blade}} = \frac{2u(V_{w1} + V_{w2} + V_{w1}' + V_{w2}')}{V_1^2} \times 100$$

$$= \frac{2 \times 108 (313.2 + 68.4 + 190.8 + 0)}{324^2} \times 100$$

$$= 0.97 = 97\%$$

Specific steam consumption (ms)

$$ms = \frac{3600}{(V_{w1} + V_{w2} + V_{w1}') u}$$

$$= \frac{3600}{(435 + 95 + 265) 150}$$

$$= \underline{\underline{0.03101 \text{ kg/wh}}}$$

[illegible]

V_1 = Absolute Velocity of Steam entering the blade, m/s

V_{A1} = relative velocity of steam at inlet, m/s

V_{w1} = whirl velocity at inlet

V_{f_1} = Velocity of flow at inlet

$V_2 =$ Absolute velocity of Steam at exit

V_{g_2} = relative velocity of Steam at exit

V_{w_2} = whirl velocity at exit

V_{f2} = velocity of flow at exit

 $\alpha = \text{Nozzle angle}$

θ = inlet angle of moving blade

ϕ = exit or outlet angle of moving blade

β = Angle of discharge at exit.

If Axial
thrust is zero

$$v_{f1} = v_{f2}$$

(a) work done on blade

From Newton's Second law of motion

Tangential force = mass $\times$ acceleration

$$= \text{mass/sec} \times \text{change in wheel velocity}$$

$$= m (v_{w1} \pm v_{w2}) \quad N$$

$$\frac{\text{kg} \cdot \text{m}}{\text{s}^2} = 1 \text{ N}$$

$$W.D/s = F \times \text{Dist. moved / sec}$$

$$\Rightarrow m(V_{w1} \pm V_{w2}) = \frac{Nm}{s} \text{ (e.g.) } \frac{5}{5}$$

Power developed, $P = m (V_{w1} \pm V_{w2}) \cdot u$ watts

m = mass of steam flowing / sec over blades

Note: use +ve sign, if V_{w1} and V_{w2} are in opposite direction, and -ve sign if V_{w1} and V_{w2} are in same direction.

(b) Blade or diagram efficiency

It is the ratio of work done on blade to the energy supplied to blade.

Blade or diagram efficiency = $\frac{\text{work done on blade}}{\text{energy supplied to blade}}$

$$= \frac{m (V_{w1} \pm V_{w2}) u}{\frac{1}{2} m V_1^2}$$

$$\eta_b = \frac{(V_{w1} \pm V_{w2}) 2u}{V_1^2}$$

(b) Nozzle efficiency

It is the ratio of kinetic energy of steam at exit of the nozzle to the enthalpy drop in nozzle.

$$\text{Nozzle efficiency} = \frac{\frac{1}{2} m V_1^2}{m \Delta h} = \frac{V_1^2}{2 \Delta h}$$

V_1 = abs. velocity of steam, m/s

Δh = enthalpy drop in nozzle, Joules.

(c) Stage efficiency

It is ratio of work done on blade to enthalpy drop in nozzle.

(2)

$$\text{Stage efficiency} = \frac{m(V_{w1} \pm V_{w2})u}{m(ah)}$$

$$\Rightarrow \frac{(V_{w1} \pm V_{w2}) 2u}{V_1^2} \times \frac{V_1^2}{2ah}$$

$$\therefore \text{Stage efficiency} = \text{Blade efficiency} \times \text{Nozzle efficiency}$$

Note: If losses in nozzle are neglected,

then, Stage η = blade η .

(d) Axial thrust:

Axial thrust on the wheel occurs when velocity of flow at inlet is not equal at outlet.

Axial Force = mass $\times$ axial acceleration

$$= m(V_{f1} - V_{f2}) \text{ N}$$

Axial thrust acts along the shaft and is absorbed by bearings.

(e) Driving force on the wheel:

$$F_x = m(V_{w1} \pm V_{w2}) \text{ N}$$

(f) Loss of energy due to friction

$$\Rightarrow \frac{V_{g1}^2 - V_{g2}^2}{2000} \text{ kJ}$$

(g) Effect of blade friction

~~The~~ In practice, some resistance is always offered by blade surface to gliding steam jet, whose effect is to reduce relative velocity of jet. i.e. to make V_{g2} less than V_{g1} .

The ratio of $\frac{V_{A2}}{V_{A1}}$ is known as blade velocity coefficient (or) coefficient of velocity (or) friction factor (k)

Blade velocity coefficient,

$$k = \frac{V_{A2}}{V_{A1}}$$

(h) Blade speed ratio:

It is ratio of blade velocity to absolute velocity of steam jet at entry to the blade.

$$\text{Blade speed ratio, } S = \frac{u}{V_1}$$

Maximum efficiency of Impulse (De Laval) Turbine:

Blades of impulse turbine are made symmetrical

i.e. $\theta = \phi$

$$\text{Energy Supplied / kg of steam} = \frac{1}{2} V_1^2$$

$$\text{Energy rejected / kg of steam} = \frac{1}{2} V_2^2$$

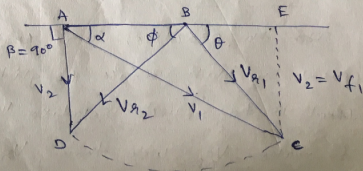
$$\text{work done per kg of steam} = \frac{V_1^2 - V_2^2}{2}$$

work done is maximum, where V_2 is minimum

i.e. when the angle, $\beta = 90^\circ$.

Neglecting friction, $V_{A2} = V_{A1}$

$\theta = \phi$ for De-Laval turbine



③

$$\angle BAD = \angle BEC = 90^\circ$$

$$AB = BE = \frac{1}{2} AE = \frac{1}{2} \cdot AC \cdot \cos \alpha$$

$$u = \frac{1}{2} \cdot V_{w1} = \frac{1}{2} \cdot V_1 \cos \alpha$$

$$\text{optimum blade speed, } s = \frac{u}{V_1}$$

$$s = \frac{V_1 \cos \alpha}{2 V_1}$$

$$s = \frac{\cos \alpha}{2}$$

$$V_2 = EC = V_1 \sin \alpha$$

$$\text{efficiency} = \frac{\text{W.D / kg of steam}}{\text{K.E Supplied / kg of steam}}$$

$$\Rightarrow \frac{\frac{V_1^2 - V_2^2}{2}}{\frac{V_1^2}{2}} \Rightarrow \frac{V_1^2 - V_2^2}{V_1^2}$$

$$\text{Maximum efficiency, } = \frac{V_1^2 - V_1^2 \sin^2 \alpha}{V_1^2}$$

$$= 1 - \sin^2 \alpha$$

$$\eta_{\max} = \cos^2 \alpha$$

$$\text{For Pelton turbine, Nozzle angle } \alpha = 20^\circ$$

$$\eta_{\max} = \cos^2 20^\circ = 0.883 = 88.3\%$$

The Above Value is only under ideal conditions.
In actual practice, the maximum efficiency of
Pelton turbine is about 55%.

Further, when $\beta = 90^\circ$, $V_{w2} = 0$

$$w.o \text{ / kg of steam} = (V_{w1}) \cdot u$$

$$\text{For max. efficiency, } V_{w1} = 2u$$

$$\text{Maximum w.o (or) power} = 2u^2 \text{ J/s (or) watts}$$

efficiency is maximum for small nozzle angle
($16^\circ - 22^\circ$)

$$\rho_{opt} =$$

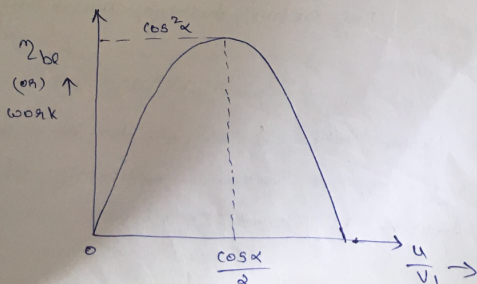
optimum value of ratio of blade speed to steam speed is

$$\rho_{opt} = \frac{\cos \alpha}{2}$$

$$\frac{u}{V_1} = \frac{\cos \alpha}{2}$$

blade velocity should be approximately half of absolute velocity of steam jet coming out from nozzle (fixed blade) for maximum work developed per kg of steam (or) for maximum efficiency.

Variation of η_{bl} (or) work developed per kg of steam with $\frac{u}{V_1}$. fig shows that

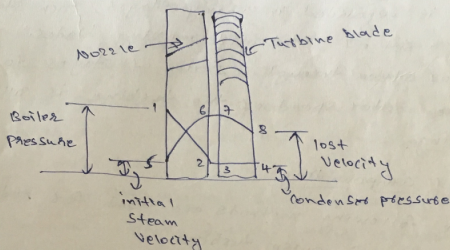


15 (4) (a) when $\frac{u}{V_1} = 0$, the work done becomes zero

(b) maximum efficiency is $\cos^2 \alpha$ and maximum work done/kg of steam is $2u^2$, when $\frac{u}{V_1} = \frac{\cos \alpha}{2}$

(c) when $\frac{u}{V_1} = 1$, work done is zero

Simple Impulse turbine



The pressure of steam jet is reduced in the nozzle and remains constant while passing through moving blade. The velocity of steam is increased in nozzle, and is reduced while passing through moving blades. In this turbine, the 'exit velocity' or leaving velocity or lost velocity, may amount to 3.3% of nozzle outlet velocity. Since all the kinetic energy is to be absorbed by one ring of moving blades only, the velocity of wheel is too high (Varying from 25000 to 30,000 rpm). Thus wheel or rotor speed can be reduced by different compounding methods.

Compounding (or) Methods of Reducing Rotor Speed

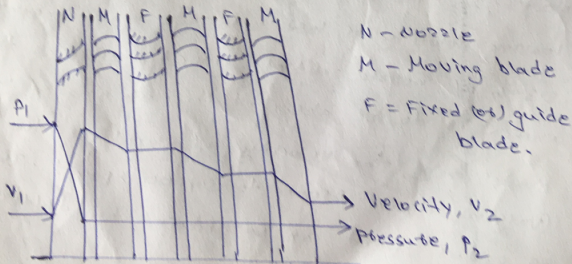
If the steam is expanded from high boiler pressure to condenser pressure, the steam velocity is extremely high and turbine speed will be very high. Such speeds are not practicable for power generation. Further there will be 10 to 12% loss in kinetic energy with single stage. To overcome these limitations, the steam is expanded in many stages, each stage comprises a set of fixed and moving blades. expansion of steam through a series of stages to reduce the rotor speed of the turbine is called Compounding.

Methods of Compounding

The following methods are used for reducing the speed of an impulse turbine.

- (a) Velocity compounding
- (b) Pressure Compounding
- (c) Velocity-pressure compounding

(a) Velocity Compounding

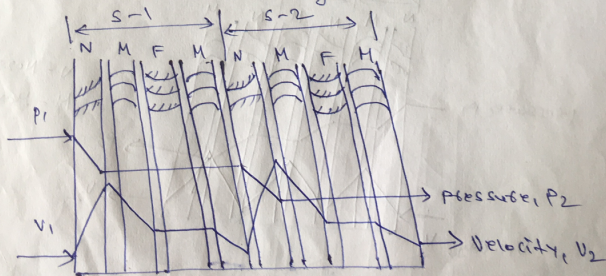


9

fig shows rings of fixed nozzles incorporated between the rings of moving blades. The steam at boiler pressure enters the first set of nozzles and expands partially. The kinetic energy of steam thus obtained is absorbed by the moving blades (Stage 1). The steam then expands partially in second set of nozzles where its pressure again falls and velocity increases; the kinetic energy so obtained is absorbed by the second ring of moving blades (Stage 2). This is repeated in Stage 3 and steam finally leaves the turbine at low velocity and pressure. The number of stages, depends on number of rows of nozzles through which steam must pass.

This method of compounding is used in Rateau and Zoelly turbine. This is most efficient turbine, since speed ratio remains constant but it is expensive owing to a large number of stages.

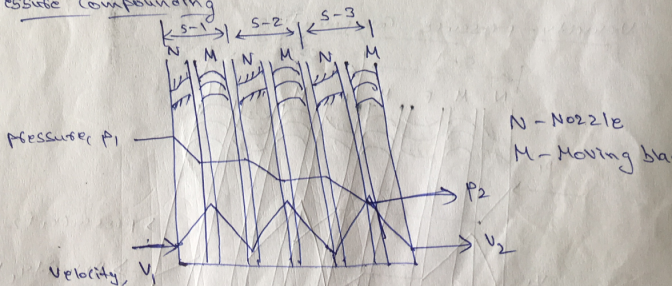
Velocity-pressure Compounding



Steam is expanded through a stationary nozzle from boiler pressure to condenser pressure. So the pressure drops in nozzle, the kinetic energy of steam increases. A portion of this available energy is absorbed by a row of moving blades. The steam (whose velocity has decreased while moving over moving blades) then flows through the second row of blades which are fixed. The function of these fixed blades is to re-direct the steam flow without altering its velocity to the following next row moving blades where again work is done on them and steam leaves the turbine with a low velocity. Above fig depicts changes in pressure and velocity as steam passes through nozzle, fixed and moving blades.

Though this method has advantage that the initial cost is low due to lesser number of stages, but its efficiency is low.

Pressure Compounding



⑦

Experiment

- ⑥ The speed of turbine may be reduced by splitting up the available energy by arranging two or more simple velocity-compounded turbines in series on the same shaft. The total drop in steam pressure is divided into stages ~~and~~ (i.e. two or more stages). and velocity obtained in each stage is also compounded. The rings of nozzles are fixed at the beginning of each stage and pressure remains constant during each stage. In this method, less stages are required for given pressure drop. But due to low efficiency, it is not widely used in power generation.

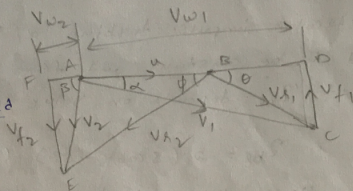
⑦

expression for
optimum value of
Ratio of blade speed
to steam speed

(for max efficiency)

for single stage

Impulse turbine.



$$V_w = V_{x1} \cos \theta + V_{x2} \cos \phi$$

$$\Rightarrow V_{x1} \cos \theta \left[1 + \frac{V_{x2} \cos \phi}{V_{x1} \cos \theta} \right]$$

$$\Rightarrow V_{x1} \cos \theta (1 + k z)$$

For impulse turbine,

$$z = \frac{\cos \phi}{\cos \theta}$$

$$\theta = \phi$$

$$z = 1$$

$$V_{x1} \cos \theta = V_1 \cos \alpha - u$$

$$V_w = (V_1 \cos \alpha - u) (1 + k z)$$

$$\text{w.h.t. } \tau = \eta_b = \frac{(V_w \pm V_w) 2u}{V_1^2}$$

$$\Rightarrow \frac{V_w \cdot 2u}{V_1^2}$$

$$\Rightarrow \frac{2u (V_1 \cos \alpha - u) (1 + k z)}{V_1^2}$$

$$\Rightarrow \frac{2(V_1 u \cos \alpha - u^2) (1 + k z)}{V_1^2}$$

$$\Rightarrow 2(s \cos \alpha - s^2) (1 + k z)$$

$$\Rightarrow 2s (\cos \alpha - s) (1 + k z)$$

$$\text{Blade speed ratio, } s = \frac{u}{V_1} = \frac{\text{Blade speed}}{\text{steam speed}}$$

$$s = 0.6192 \text{ (or) } 0.3208$$

(8)

For particular impulse turbine α , k and z may assumed to be constant and from equation it is seen that η_{bl} depends on value of s only.

$$\eta_{bl} = 2(s \cos \alpha - s^2)(1+kz) \quad \text{--- (i)}$$

Hence differentiating w.r.t s & equate to zero for maximum value.

$$\frac{d\eta_{bl}}{ds} = 2(\cos \alpha - 2s)(1+kz) = 0$$

$$\cos \alpha - 2s = 0$$

$$\therefore \cos \alpha = 2s$$

$$s = \frac{\cos \alpha}{2}$$

optimum value of ratio of blade speed to stream speed is

$$\boxed{s_{opt} = \frac{\cos \alpha}{2}} \quad \text{--- (ii)}$$

Substituting eq (ii) in eq (i)

$$\eta_{bl, \max} = 2 \times \frac{\cos \alpha}{2} \times \left(\cos \alpha - \frac{\cos \alpha}{2} \right) (1+kz)$$

$$\eta_{bl} = 2s(\cos \alpha - s)(1+kz)$$

$$(\eta_{bl})_{\max} = 2 \times \frac{\cos \alpha}{2} \left(\cos \alpha - \frac{\cos \alpha}{2} \right) (1+kz)$$

$$\Rightarrow \cos \alpha \cdot \frac{\cos \alpha}{2} (1+kz)$$

$$\boxed{\eta_{bl, \max} \rightarrow \frac{\cos^2 \alpha}{2} (1+kz)}$$

- ⑧ Assume symmetrical blades ($\theta = \phi$) and no friction in fluid passage

$$z = 1, k = 1$$

$$(\eta_{bl})_{\max} = \cos^2 \alpha$$

From eq (ii) it is obvious that blade velocity should be approximately half of absolute velocity of steam jet coming out from the nozzle for maximum work developed per kg of steam or for maximum efficiency. For other values of blade speed the absolute velocity at outlet from the blade will increase, hence more energy will be carried away by steam and efficiency will decrease.

The Variations of η_{bl} or work developed per kg of steam with $\frac{u}{V_1}$. This fig shows that

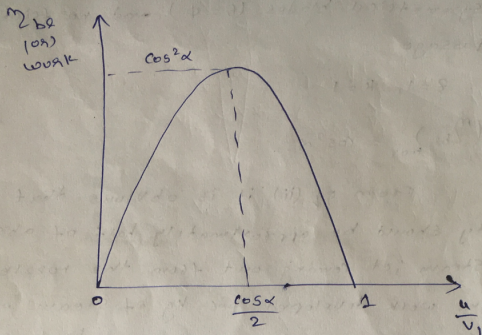
(a) when $\frac{u}{V_1} = 0$, the work done becomes zero as the distance travelled by the blade (u) is zero.

(b) Maximum efficiency is $\cos^2 \alpha$ and maximum work done per kg of steam is $2u^2$, when

$$\frac{u}{V_1} = \frac{\cos \alpha}{2}$$

(c) when $\frac{u}{V_1} = 1$, the work done is zero as the torque acting on the blade becomes zero.

Fig 2.11



Work done per kg of steam is given by

$$W = m (V_{w1} + V_{w2}) u$$

$$V_w = V_{w1} + V_{w2}$$

$$W = V_w \cdot u = (V_1 \cos \alpha - u) (1 + k) \cdot u$$

$$\Rightarrow \text{When } k=1, z=1$$

$$\Rightarrow 2u (V_1 \cos \alpha - u)$$

$$s = \frac{\cos \alpha}{2}$$

$$W_{\max} = 2u (2s - u)$$

$$\cos \alpha = 2s$$

$$\cos \alpha = 2 \cdot \frac{u}{V_1}$$

$$W_{\max} = 2u (V_1 \cdot 2 \cdot \frac{u}{V_1} - u)$$

$$\Rightarrow 2u (2u - u)$$

$$\Rightarrow 2u^2 \cdot (2 - 1)$$

$$\Rightarrow 2u (u)$$

$$W_{\max} \rightarrow 2u^2$$

ISA] ⑨

$$\theta = \phi$$

$$\alpha = 20^\circ$$

$$k = \frac{V_{A2}}{V_{A1}} = 0.83$$

Actual blade efficiency = 90% of maximum blade efficiency.

$$s = \frac{u}{V_1} = ?$$

Maximum blade efficiency

$$(\eta_{bl})_{\max} = \frac{\cos^2 \alpha}{2} (1+k)$$

$$\Rightarrow \frac{\cos^2 \alpha}{2} (1+k) \quad z = \frac{\cos \phi}{\cos \theta} = 1$$

$$k = 0.83$$

$$(\eta_{bl})_{\max} = \frac{\cos^2 20^\circ}{2} (1+0.83) \times 100$$

$$= 80.79\%$$

Actual efficiency of turbine

$$\eta_{bl} = 0.9 \times 80.79 = 72.71\%$$

Blade efficiency of a single stage impulse turbine is given by relation

$$\eta_{bl} = 2 (s \cos \alpha - s^2) (1+k)$$

$$0.727 = 2 (s \times \cos 20^\circ - s^2) (1+0.83)$$

$$0.727 = 2 \times 1.83 (0.945 - s^2)$$

$$0.19863 = 0.945 - s^2$$

$$s^2 - 0.945 + 0.19863 = 0$$

$$s = \frac{0.94 \pm \sqrt{(0.94)^2 - 4 \times 0.19863}}{2}$$

$$s \Rightarrow \frac{0.94 \pm 0.2984}{2}$$

$$\Rightarrow \text{Hence possible ratio is } s = 0.6192 \text{ (or) } 0.3208$$

16A]

$$V_1 = 300 \text{ m/s}$$

$$\alpha = 25^\circ$$

$$D = 100 \text{ cm} = 1 \text{ m}$$

$$N = 2000 \text{ rpm}$$

$$\text{Scale: } 1 \text{ cm} = 50 \text{ m/s}$$

$$\text{Axial thrust, } F_a = m(V_{f1} - V_{f2}) = 0$$

$$(V_{f1} = V_{f2})$$

To find:

$$\theta = ?$$

$$\phi = ?$$

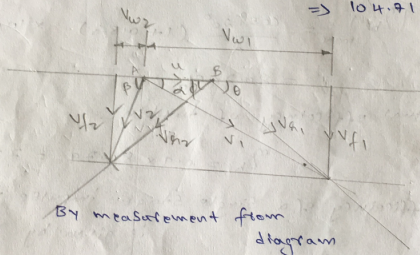
$$P = ?$$

$$m = 600 \frac{\text{kg}}{\text{min}}$$

$$k = 0.9 = \frac{V_{A2}}{V_{A1}}$$

$$\text{Blade speed, } u = \frac{\pi DN}{60} = \frac{\pi \times 1 \times 2000}{60}$$

$$\Rightarrow 104.71 \text{ m/s}$$



$$V_{A1} = 215 \text{ m/s}$$

$$V_{A2} = 193.5 \text{ m/s}$$

By measurement from diagram

$$\theta = 37^\circ$$

$$\phi = 43^\circ$$

$$\text{Power developed, } P = \frac{m(V_{w1} + V_{w2})u}{1000} \text{ kW}$$

$$= \frac{600 \times 310 \times 104.71}{60 \times 1000} \text{ kW}$$

$$\Rightarrow 324.601 \text{ kW}$$

9A]

(10)

$$V_1 = 840 \text{ m/s}$$

$$\alpha = 18^\circ$$

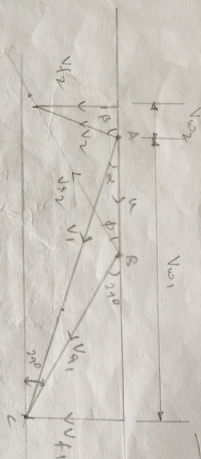
$$\theta = \phi = 29^\circ$$

$$k = 0.9 = \frac{V_{A2}}{V_{A1}}$$

$$P = 300 \text{ kW}$$

To find: (a) $u = ?$

$$(b) m = ? (\text{kg/h}_2)$$



Scale: $1 \text{ cm} = 100 \text{ m/s}$

$$V_{A1} = 540 \text{ m/s}$$

$$V_{A2} = 486 \text{ m/s}$$

$$(c) u = 840 \text{ m/s}$$

$$(b) P = \frac{m (V_{u1} + V_{u2}) u}{1000} \text{ kW}$$

$$300 = \frac{m (880) \times 840}{1000}$$

$$m = 1 \text{ kg/sec} = 3600 \text{ kg/h}_2$$

12 A]

$$P = 132.4 \text{ kW}$$

$$u = 175 \text{ m/s}$$

$$m = 2 \text{ kg/sec}$$

$$V_1 = 400 \text{ m/s}$$

$$k = \frac{V_{R1}}{V_{R1}} = 0.9$$

$$\text{Scale: } 1 \text{ cm} = 50 \text{ m/s}$$

[Discharge is axial

$$\beta = 90^\circ, V_{w2} = 0]$$

To find:

$$\alpha = ?$$

$$\theta = ?$$

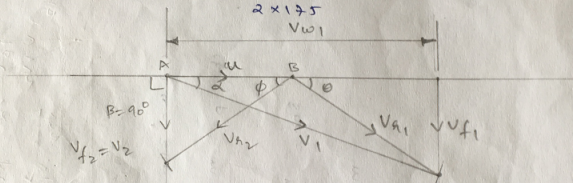
$$\phi = ?$$

Power developed

$$P = \frac{m (V_{w1} + V_{w2}) u}{1000} \text{ kW}$$

$$132.4 = \frac{2 (V_{w1} + V_{w2}) 175}{1000}$$

$$V_{w1} + V_{w2} = \frac{132.4 \times 1000}{2 \times 175} \Rightarrow 378.28 \text{ m/s}$$



From diagram, (by measurement)

$$\alpha = 21^\circ$$

$$\theta = 36^\circ$$

$$\phi = 32^\circ$$

$$V_{R1} = 240 \text{ m/s}$$

$$V_{R2} = 216 \text{ m/s}$$

7A)

(11)

$$\alpha = 20^\circ$$

$$V_1 = 670 \text{ m/s}$$

$$\theta = 35^\circ$$

$$\theta = \phi = 35^\circ$$

To find:

$$u = ?$$

$$\eta_b = ?$$

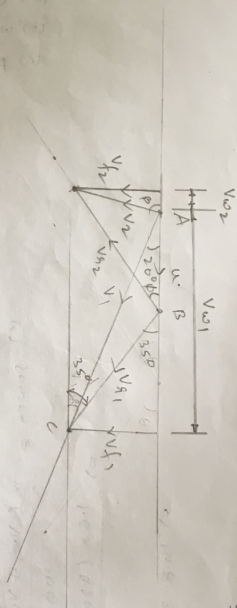
$$(a) u = 280 \text{ m/s}$$

(b) Diagram efficiency

$$\eta_b = \left[\frac{(V_{w1} + V_{w2}) \cdot 2u}{V_1^2} \right] \times 100$$

$$\Rightarrow \left[\frac{680 \times 2 \times 280}{(670)^2} \right] \times 100$$

$$\Rightarrow 84.8\%$$



Scale, $1 \text{ cm} = 100 \text{ m/s}$

14A

2A)

$$\alpha = 20^\circ$$

$$\dot{V}_1 = 450 \text{ m/s}$$

$$\phi = 20^\circ$$

$$V_{x2} = V_{x1}$$

$$u = 180 \text{ m/s}$$

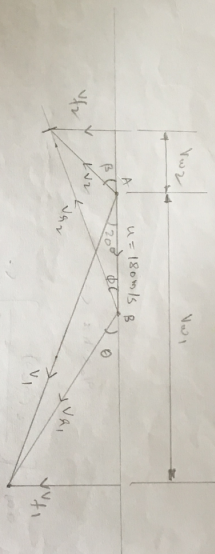
$$m = 1.6 \text{ kg/s}$$

To find:

(a) θ

(b) w.d/kg

(c) power



$$(a) \theta = 32^\circ$$

$$(b) \text{ w.d/kg} = \frac{m(V_{u1} + V_{u2})}{1000} \text{ kg/kg}$$

$$\Rightarrow \frac{1 \times (420 + 95) \times 180}{1000} \text{ kg/kg}$$

$$\Rightarrow 92.7 \text{ kg/kg}$$

$$(c) \text{ power} = \frac{m(V_{u1} + V_{u2})}{1000} \text{ kW}$$

$$\Rightarrow \frac{1.6 \times (420 + 95) \times 180}{1000}$$

$$\Rightarrow 148.32 \text{ kW}$$

Scale: 1 cm = 50 m/s

1. Steam with a velocity of 600 m/s enters the row of blades
(12) of an impulse turbine. The blade angle at entry is 25° .
The mean blade speed is 250 m/s. The exit angle of blade is
 30° . There is 10% loss in relative velocity due to friction
in the blades. Determine.

- (a) Nozzle angle (b) work done per kg of steam
(c) Diagram efficiency (d) Axial thrust per kg of steam.

Ans:

$$V_1 = 600 \text{ m/s}$$

$$\theta = 25^\circ$$

$$u = 250 \text{ m/s}$$

$$\phi = 30^\circ$$

$$k = \frac{V_{R2}}{V_{R1}} = 0.9$$

Scale : 1 cm = 100 m/s

$\alpha = 15^\circ$

$250 \times 100 \text{ m/s}$

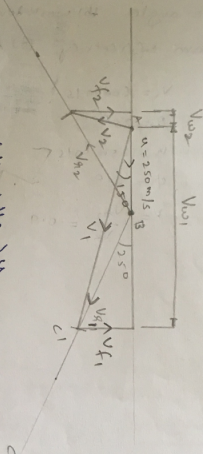
$\alpha = 15^\circ$

$$V_{h1} = 3.7 \text{ cm} \times 100$$

$$\Rightarrow 370 \text{ m/s}$$

$$V_{h2} = 0.9 \times 370$$

$$\Rightarrow 333 \text{ m/s}$$



$$(a) \text{ w.d } | \text{ kg} = \frac{m (V_{w1} + V_{w2})}{1000} \text{ Ks/kg}$$

$$\Rightarrow \frac{1 \times (570 + 50) \times 250}{1000} = 155 \text{ Ks/kg}$$

$$(b) \text{ Diagram efficiency } (\eta_b) = \frac{(V_{w1} + V_{w2}) \cdot 2u}{V_{1,2}}$$

$$\Rightarrow \left[\frac{620 \times 2 \times 250}{6002} \right] \times 100 = 86\%$$

(c) Axial thrust per kg of steam

$$F_a = m (V_{f2} - V_{f1}) = 1 \times (20) = 20 \text{ N}$$

14A

(13)

$$V_1 = 450 \text{ m/s}$$

$$\alpha = 15^\circ$$

$$\phi = 30^\circ$$

$$\phi' = 30^\circ$$

$$\alpha' = 20^\circ$$

$$k = 0.9 = \frac{V_{g2}}{V_{g1}}$$

$$\frac{V_1}{V_2} = 0.9$$

$$\frac{V_{g2}}{V_{g1}} = 0.9$$

To find

a) $u = ?$

b) $\eta_{bl} = ?$

c) $m_s = ?$

Measure V_1 from inlet velocity triangle

$$V_1 = 13.5 \text{ cm} = 450 \text{ m/s}$$

Scale is now calculated as

$$\text{Scale, } 1 \text{ cm} = \frac{450}{13.5} = 33.3 \text{ m/s}$$

(a) Blade Velocity (u)

$$u = 3 \times 33.3 = 100 \text{ m/s}$$

(b) Blade efficiency, (η_{bl})

$$\eta_{bl} = \frac{\text{Rotor output}}{\text{K.E. Supplied to blade}} \times 100$$

$$\Rightarrow \frac{m' (V_{w1} + V_{w2}) u}{\frac{1}{2} m' V_1^2} = \frac{2u (V_{w1} + V_{w2})}{V_1^2}$$

$$\eta_{bl} = \frac{2u (V_{w1} + V_{w2} + V_{w'})}{V_1^2} \times 100$$

$$\Rightarrow \frac{2 \times 100 ((12.9 \times 33.3) + (5.3 \times 33.3) + (6 \times 33.3))}{(450)^2} \times 100$$

$$\Rightarrow 79.6\%$$

(c) Specific Steam Consumption, m_s

$$m_s = \frac{3600}{(V_{w0} + V_{w'}) u} \text{ kg/wh}$$

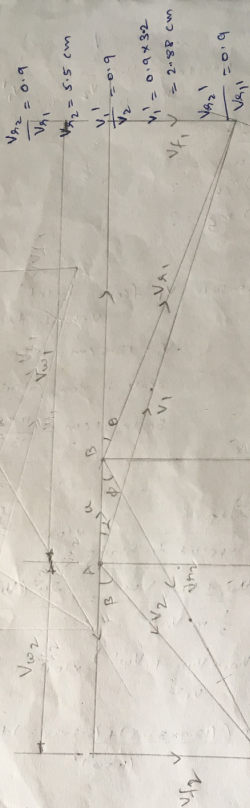
$$V_{w0} = V_{w1} + V_{w2}$$

$$\Rightarrow \frac{3600 \times 1000}{(V_{w0} + V_{w'}) u} = \text{--- kg/kwh}$$

Assume, $u = 3 \text{ cm}$

$1 \text{ cm} = 50 \text{ m/s}$

First row of moving blades



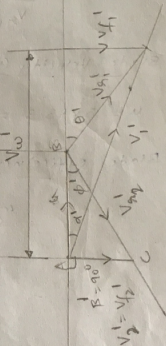
$\Rightarrow 3.88 \text{ cm}$

$$V_2 = \frac{6.4}{0.9}$$

$$\Rightarrow 7.11 \text{ cm}$$

$$V_{a1} = \frac{9.6}{0.9}$$

$$\Rightarrow 10.66 \text{ cm}$$



Second row of moving blades